B. Tech thesis on

STUDY OF DRAG COEFFICIENT USING CFD TOOLS

For partial fulfilment of the requirements for the degree of

Bachelor of Technology

in

Chemical Engineering

Submitted by:

Varsa Priyadarshini

Roll Number- 108CH045

Under the guidance of:

Prof Basudeb Munshi

Department of Chemical Engineering,

National Institute of Technology,

Rourkela-769008

CERTIFICATE

This is to certify that the thesis entitled "**Study of Drag Coefficient Using CFD Tools**" submitted by **Varsa Priyadarshini (108CH045)** in partial fulfilment of the requirements for the award of degree of Bachelor of Technology in Chemical Engineering at National Institute of Technology, Rourkela is an authentic work carried out by her under my supervision and guidance.

To best of knowledge, the matter embodied in this thesis has not been submitted to any other university or institute for the award of any degree.

Date:

Place: Rourkela

Prof Basudeb Munshi

Department of Chemical Engineering,

National Institute of Technology,

Rourkela-769008

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I thank my family and friends for being constant support throughout my life.

Date:

Place: Rourkela

Varsa Priyadarshini

Roll Number-108CH045

Department of Chemical Engineering,

NIT, Rourkela-769008

ABSTRACT

Flow over cylinder is frequently encountered in practice. The objective of this project is modelling and simulation of the flow over a cylinder by using CFD techniques in order to study the values of drag coefficient at different Reynolds number ranging from 1 to 100 at a given Length to Diameter ratio (L/D). Different length to diameter ratio (L/D) of cylinder is considered, ranging from 0.005 to 1 is taken. Study of the variation of drag coefficient at different L/D ratios of the cylinder at a constant Reynolds has been done graphically. Comparison of the values of drag coefficient at L/D equal to one with that of the sphere has been done graphically and discussed. Analysis and discussion of the flow over the cylinder at varying Reynolds number and different L/D ratios using velocity contours, pressure contours, streamlines and vorticity plots.

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NOMENCLATURE

ρ	Density
A	Projected area
C_d, C_x, C_w	Drag coefficient
D	Diameter of cylinder
F_d	Drag force
L	Length of cylinder
Re	Reynolds number
v	Velocity

1. INTRODUCTION

Whenever a difference in velocity exists between a particle and its surrounding fluid, the fluid will exert a resistive force on the particle. Either the gas may be at rest and the particle moving through it or the particle may be at rest and the fluid flowing past it. It is generally immaterial which phase is assumed to be at rest; it is the relative velocity between the two that is important. The resistive force exerted by the fluid on the particle is called drag.

The drag coefficient (commonly denoted as C_d , C_x or C_w) is a dimensionless quantity that is used to quantify the drag or resistance of an object in a fluid environment. The drag coefficient is always associated with a particular surface area.

The drag coefficient C_d is defined as: $C_d = (2\, F_d\, A/\, \rho\, v^2)$

From dimensional analysis, the drag coefficient of a smooth solid in an incompressible fluid depends on Reynolds number and necessary shape ratios.

Drag is generally divided into following types:

i. Parasitic drag (also called skin friction drag): It is the drag caused by moving a solid object through a fluid medium (in the case of aerodynamics, more specifically, a gaseous medium). Parasitic drag is made up of many components, the most prominent being form drag. Skin friction and interference drag are also major components of parasitic drag.

ii. Lift-induced drag: It is a drag force that occurs whenever a moving object redirects the airflow coming at it.

iii. Wave drag: It is a component of the drag on aircraft blade tips and projectiles moving at transonic and supersonic speeds, caused by the formation of shock waves around the body.

Objective:

The objective of this project is modelling and simulation of the flow over a cylinder by using CFD techniques in order to study the values of drag coefficient at different Reynolds number ranging from 1 to 100 at different Length to Diameter ratios (L/D).

2. LITERATURE REVIEW

2.1 NECESSITY OF EVALUATION OF DRAG COEFFICIENT:

Evaluation of drag force on a particle placed in moving fluid streams is necessary in wide range of applications like chemical, mineral and process industries. Typical examples include process design calculation for continuous processing of large food particles, fixed and fluidized bed reactors, pneumatic and hydraulic conveying of coarse particles, liquid solid separation and classification technique etc. (Chhabra R.P. et al. 1998)

The settling behaviour for variously shaped particles is of fundamental importantance. Irregularly shaped particles are met in many applications, such as sedimentation and flocculation of aggregates of fine particles in rivers and lakes, chemical blending, mineral processing, powder sintering, manufacturing with phase change and solidification processes. In most of these applications, the determination of the falling velocity of the particle is of interest for the design and optimization of processes and equipment. Since the falling velocity of a particle depends greatly on its drag coefficient, reliable correlations for the drag coefficient of the particles are necessary (Tran-Cong Sabine et al. 2003)

Many processes for the separation of particles of different sizes and shapes depend upon variations in the behaviour of the particles when subjected to the action of a moving fluid. A particle falling in an infinite fluid under the influence of gravity will accelerate until the gravitational force is exactly balanced by the resistance force that includes buoyancy and drag. The constant velocity reached at that stage is called the terminal velocity. The resistive drag force depends upon an experimentally determined drag coefficient. Drag coefficients along with terminal velocities is important design parameters in many separation processes (Gabitto J. 2007).

Flow over cylinder is frequently encountered in practise. The tubes in a shell and tube heat exchanger involve both internal flow through the tubes and external flow over the tubes, and both the tubes must be considered in the analysis of the heat exchanger. (Cengel Y.A, Cimbala J.M, Fluid Mechanics, Tata McGraw-Hill Education)

2.2 COMPUTATIONAL FLUID DYNAMICS (CFD):

CFD is the analysis of systems involving fluid flow, heat transfer, mass transfer, chemical reactions and related phenomena by solving mathematical equations which govern the processes using a numerical method. By means of computer based simulations. CFD is one of the branches of fluid mechanics that uses numerical methods and algorithms to solve and analyse problems that involve fluid flows. Computers are used to perform the calculations required to simulate the interaction of fluids and gases with the complex surfaces defined by boundary condition used in engineering. However, even with simplified equations and high speed supercomputers, only approximate solutions can be achieved in many cases. More accurate codes that can accurately and quickly simulate even complex scenarios such as supersonic or turbulent flows are an on-going area of research.

The fundamental basis of any CFD problem is the Navier-Stokes equations, which define any single-phase fluid flow. These equations can be simplified by removing terms describing viscosity to yield the Euler equations. Further simplification, by removing terms describing vorticity yields the Full Potential equations. Finally, these equations can be linearized to yield the Linearized Potential equations

2.3 APPLICATIONS OF CFD:

i. CFD can be used to simulate the flow over a vehicle. For instance, it can be used to study the interaction of propellers or rotors with the aircraft fuselage.
ii. Bio-medical engineering is a rapidly growing field and uses CFD to study the circulatory and respiratory systems.
iii. CFD is attractive to industry since it is more cost-effective than physical testing. However,one must note that complex flow simulations are challenging and error-prone and it takes alot of engineering exp ertise to obtain validated solutions.
iv. Meterorology: weather prediction
v. Electrical and electronics engineering: cooling of equipment including microcircuits
vi. Chemical process engineering: mixing and separation, polymer moulding

2.4 PRACTICAL ADVANTAGES OF EMPLOYING CFD:

CFD predicts performance before modifying or installing systems: Without modifying and/or installing actual systems or a prototype, CFD can predict which design changes are most crucial to enhance performance.

CFD Saves Cost and Time: CFD costs much less than experiments because physical modifications are not necessary.

CFD is Reliable: The numerical schemes and methods upon which CFD is based are improving rapidly, so CFD results are increasingly reliable. CFD is a dependable tool for design and analyses.

2.5 LIMITATIONS OF CFD:

Despite advantages, there are few shortcomings of it as follows (Bakker., 2002)

i. CFD solutions rely upon physical models of real world processes.
ii. Solving equations on a computer invariably introduces numerical errors.
iii. Truncation errors due to approximation in the numerical models.
iv. Round-off errors due to finite word size available on the computer.
v. The accuracy of the CFD solution depends heavily upon the initial or boundary conditions provided to numerical model.

2.6 ANSYS:

ANSYS is a finite element analysis (FAE) code widely used in computer-aided engineering (CAE) field. ANSYS software helps to construct computer models of structures, machine components or systems; apply operating loads and other design criteria; and study physical responses such as stress levels,temperature distributions, pressure etc.

In the above software the following basic procedure is followed:

1. During preprocessing

   The geometry (physical bounds) of the problem is definied.

The volume occupied by the fluid is divided into the discrete cells (the mesh). The mesh may be uniform or non-uniform.

The physical modelling is defined, for example, the equations of motion + enthalpy + radiation + species conversion

Boundary conditions are definied. This involves specifying the fluid behaviour of the problem. For transient problems, boundary conditions are also definied.

2. The simulation is started and the equations are solved iteratively as a steady-state or transient.
3. Finally a post-processor is used for the analysis and visualation of the resulting problem.

2.7 FLOW OVER CYLINDER:

The nature of the flow across a cylinder strongly affects drag coefficient. Both frictional drag and pressure drag can be significant. The high pressure in the vicinity of stagnation point and the flow pressure on the opposite point in the wake produce a net force on the body in the direction of flow.

Drag is due to frictional drag at low Reynolds number ($Re \leq 10$) and to pressure drag at high Reynolds number ($Re \geq 5000$). And in intermediate region both the forces are significant.

3. MODELING AND SIMULATION

3.1 PROBLEM DESCRIPTION:

Evaluation of value of drag coefficient at different Reynolds number by simulating the flow over cyclinder with different Length to Diameter (L/D) ratios and to study the behaviour of drag coefficient at different Reynolds number for each cylinder. To study the behaviour of drag coefficient at different Reynolds number for a given L/D ratio. And comparision of Reyolds number versus Drag coefficient value of cyclinder with L/D equal to 1 and that of a sphere. For evaluation of values of drag coefficient of sphere at different Reynolds number.

3.2 CFD SIMULATION OF CYLINDER:

3.2.1 Geometry and Mesh:

Geometrical modeling is one of the most critical stages in CFD simulation; correct definition of the geometry provides a more realistic scenario for the simulation, and the technique used for constructing the geometry will ensure the feasibility of generating a mesh good enough to capture all of the phenomena involved in the problem (Salari D.et al, 2007)

ANSYS FLUENT 13 was used for making 3D geometry of cyclinder with different L/D ratios. First for L/D of 1 the diameter was taken to be 1. Hence the length of the cyclinder is 0.05. A cylindrical flow domain is taken of diameter 10m and length 15m. The length is taken to be 2.5m in upstream and 12.5 in downstream as any further increase in any direction produced no change in drag coefficient values. Coarse mesh size of 1.0267m was taken in order to have 15691 nodes (85285 elements) for the whole geometry. Then named selection was done for the entire geometry.

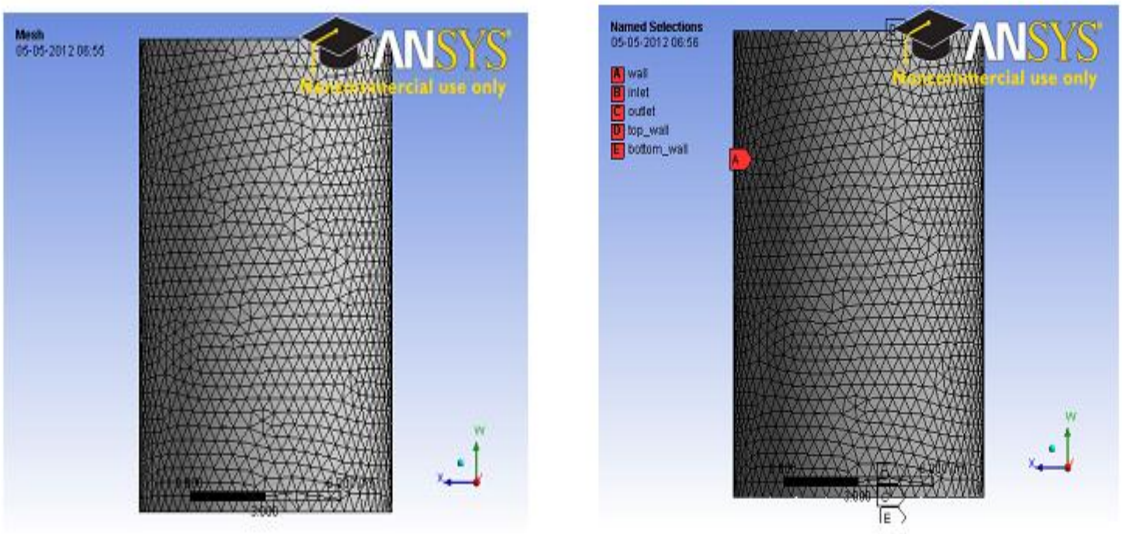

Figure 1: Meshing and Name Selection of Meshing

3.2.2 Problem Set Up:

ANSYS® FLUENT® v13 was used for simulation. In solver, pressure-based type was selected and absolute velocity formulation and steady time was selected. In viscous model, laminar was selected. And in selection of fluid, a fluid of density 1kg/m^3 was taken. The inlet velocity is taken as 1m/s and diameter of the cylinder is 1m. So accordingly viscosity of the fluid was changed at different Reynolds number using the formula $Re = \rho Dv/\mu$.

3.2.3 Solution:

Pressure-Velocity Coupling was chosen as Phase Coupled SIMPLE. First Order Upwind was chosen for Discretization. The under relaxation factor for solution control in different flow quantities were taken as pressure= 0.3, Density= 1, Body Force= 1, Momentum= 0.7. the solution was initialised. Iterations were carried out for Reynolds number 100. The solution converges after 82 iterations. The following figure shows the residual plot for the above iterations:

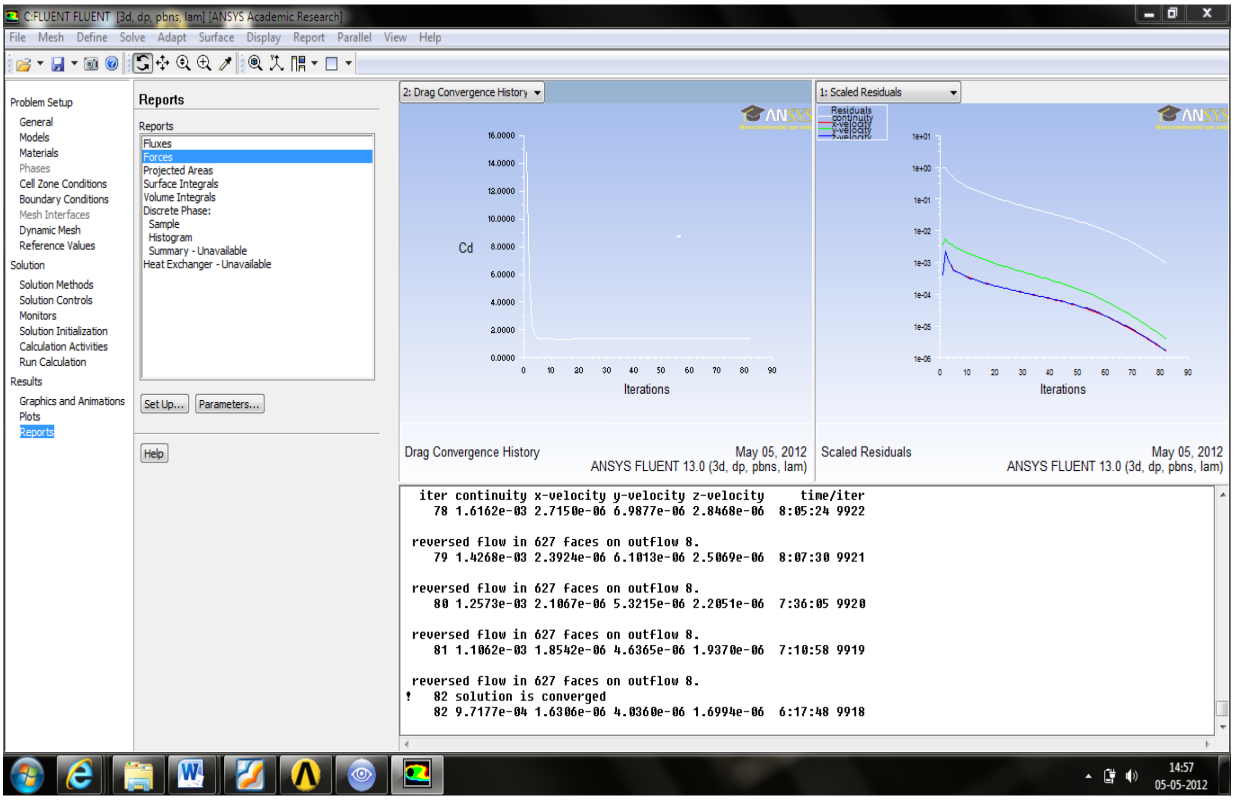

Figure 2: Drag Conversion

A convergence criteria of 0.001 has been used in the simulation. And from results the value of drag coefficient is printed from the reports.

In a similar manner iterations were done for all other reynolds number for L/D of 1 and the value of drag coefficient can be known.

Then drag coefficient value is evaluated at different reynolds number for different L/D ratio of the cyclinder ranging from a value of 0.005 to 1.

4. RESULTS AND DISCUSSION

Table 1: Values of drag coefficient at different Reynolds number ranging from 1 to 100 for L/D=0.005

Re	C_d
1	33.1
1.5	18.13
2	14.35
4	8.47
8	5.25
10	4.48
20	3.07
30	2.52
40	2.67
50	2.11
60	2.01
70	1.93
80	1.87
90	1.81
100	1.78

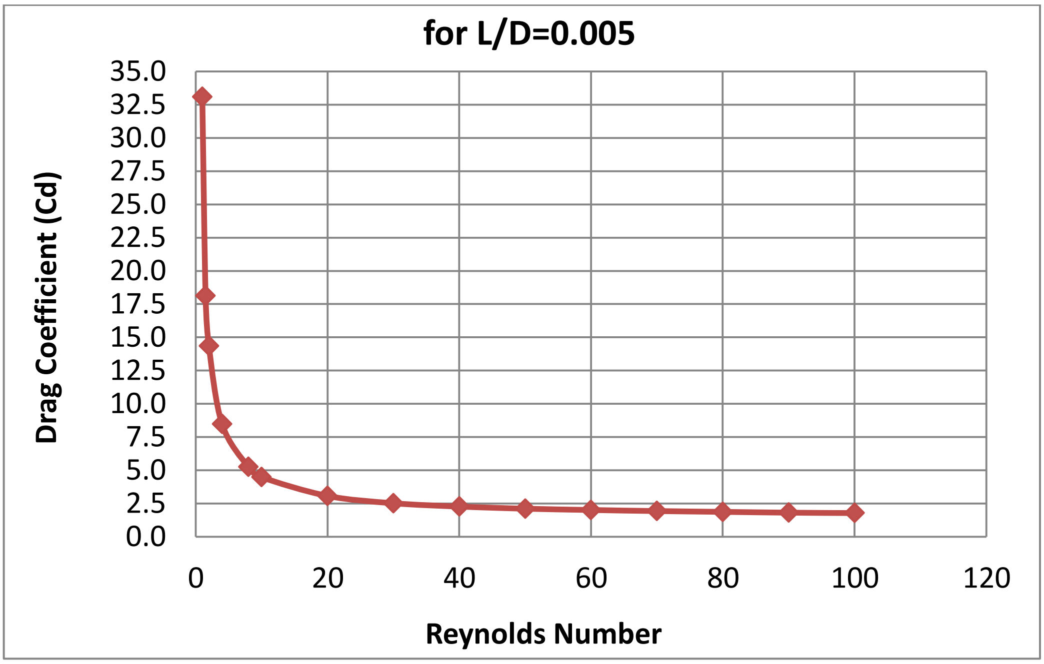

Figure 3: Variation of drag coefficient with Reynolds number al L/D =0.005

From the graph for L/D=0.005 we can conclude, the value of drag coefficient decreases with an increase in the value of Reynolds number.

Table 2: Values of drag coefficient at different Reynolds number ranging from 1 to 100 for L/D=0.01

Re	C_d
1	25.66
1.5	18.02
2	14.22
4	8.38
8	5.13
10	4.43
20	2.98
30	2.48
40	2.34
50	2.08
60	1.98
70	1.9
80	1.84
90	1.79
100	1.75

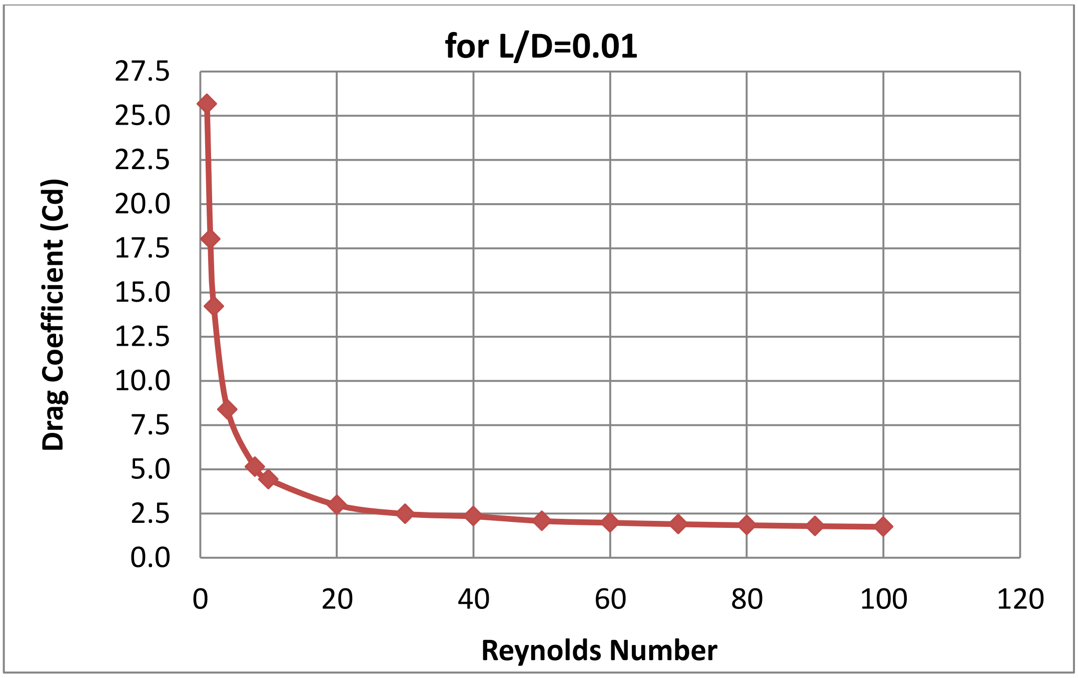

Figure 4: Variation of drag coefficient with Reynolds number al L/D =0.01

From the graph for L/D=0.01 we can conclude, the value of drag coefficient decreases with an increase in the value of Reynolds number.

Table 3: Values of drag coefficient at different Reynolds number ranging from 1 to 100 for L/D=0.05

Re	C_d
1	23.84
1.5	16.76
2	13.24
4	7.8
8	4.76
10	4.16
20	2.77
30	2.31
40	2.09
50	1.95
60	1.86
70	1.8
80	1.74
90	1.7
100	1.67

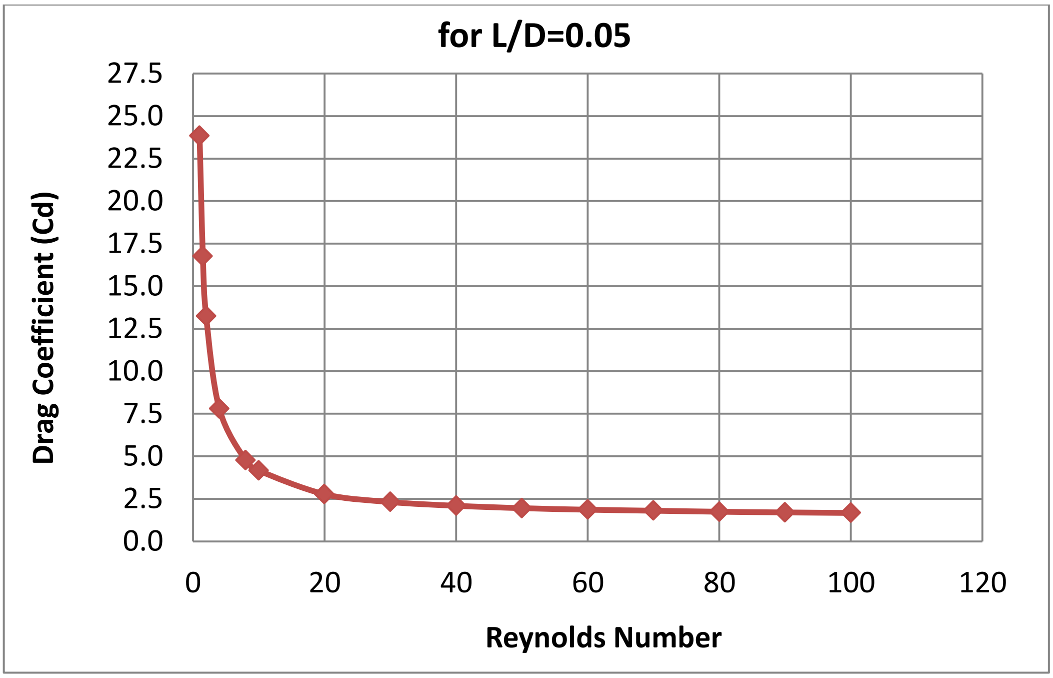

Figure 5: Variation of drag coefficient with Reynolds number al L/D =0.05

From the graph for L/D=0.05 we can conclude, the value of drag coefficient decreases with an increase in the value of Reynolds number.

Table 4: Values of drag coefficient at different Reynolds number ranging from 1 to 100 for L/D=0.1

Re	C_d
1	23.68
1.5	16.61
2	13.07
4	7.64
8	4.64
10	3.99
20	2.67
30	2.23
40	2.01
50	1.89
60	1.79
70	1.73
80	1.68
90	1.65
100	1.62

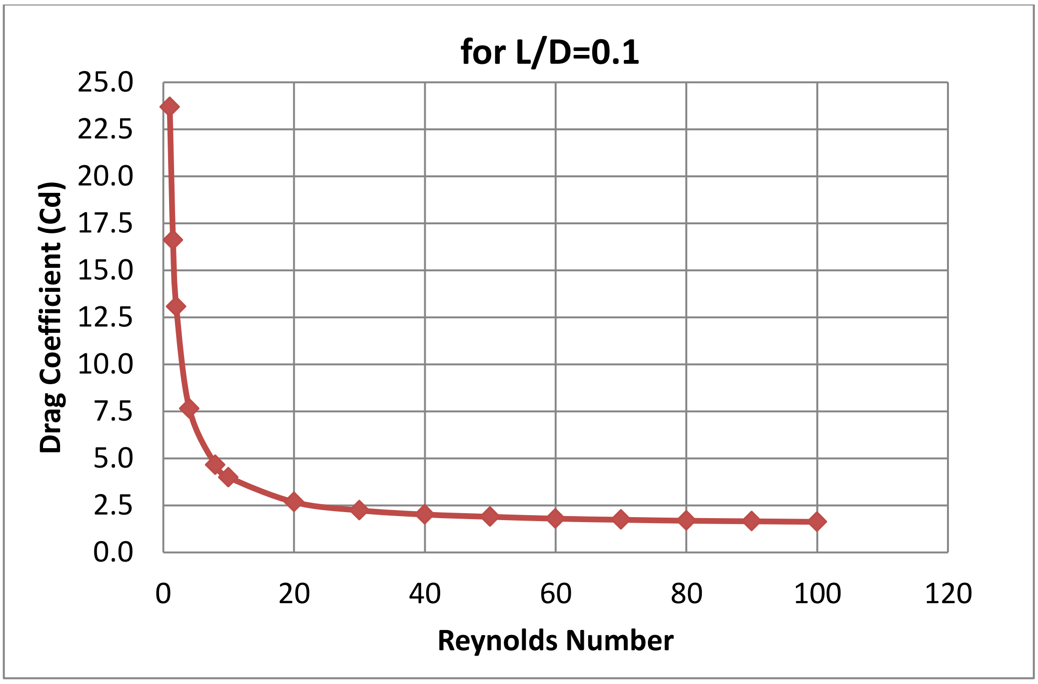

Figure 6: Variations of drag coefficient with Reynolds number al L/D =0.1

Table 5: Values of drag coefficient at different Reynolds number ranging from 1 to 100 for L/D=0.2

Re	**C_d**
1	21.81
1.5	15.29
2	12.02
4	7.03
8	4.29
10	3.7
20	2.51
30	2.11
40	1.91
50	1.79
60	1.72
70	1.66
80	1.61
90	1.58
100	1.55

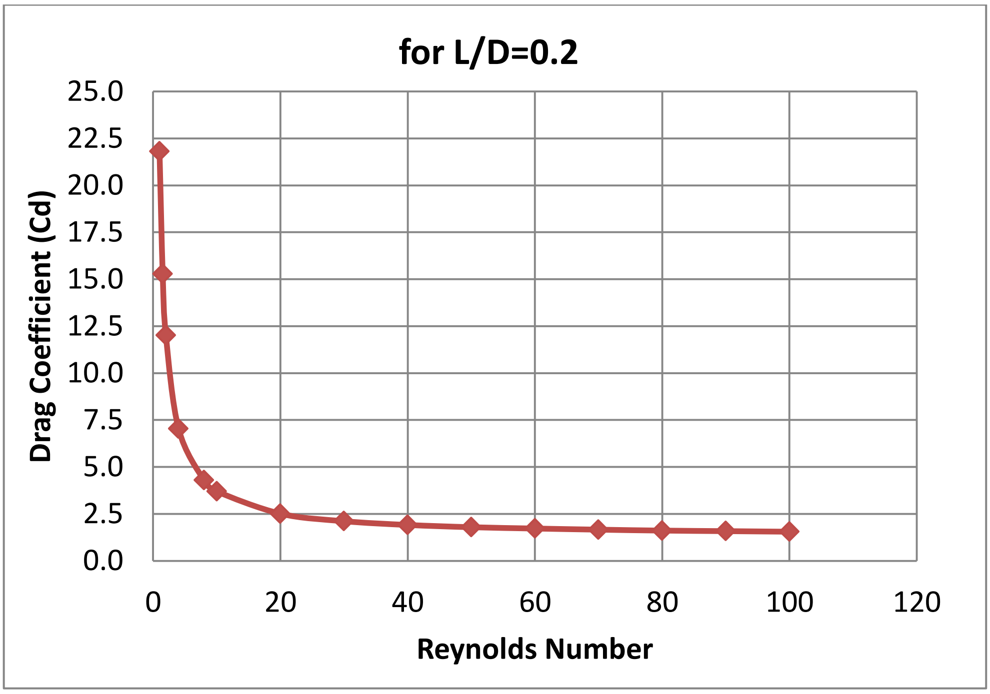

Figure 7: Variations of drag coefficient with Reynolds number al L/D =0.2

From the graph for L/D=0.2 we can conclude, the value of drag coefficient decreases with an increase in the value of Reynolds number

Table 6: Values of drag coefficient at different Reynolds number ranging from 1 to 100 for L/D=0.3

Re	C_d
1	22.09
1.5	15.5
2	12.2
4	7.14
8	4.35
10	3.75
20	2.52
30	2.11
40	1.91
50	1.79
60	1.7
70	1.64
80	1.59
90	1.56
100	1.53

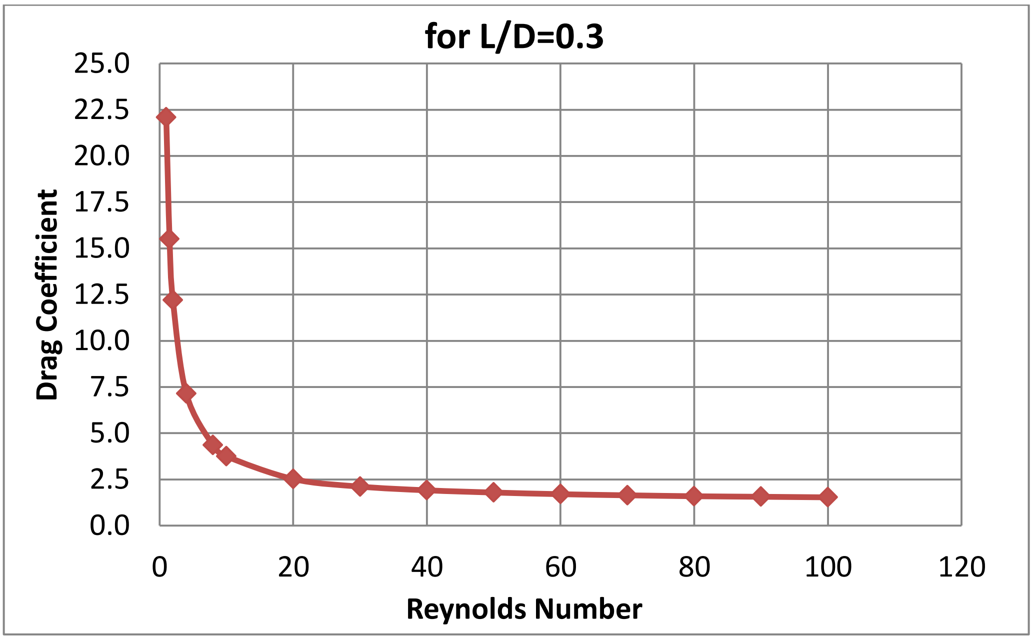

Figure 8: Variations of drag coefficient with Reynolds number al L/D =0.3

From the graph for L/D=0.3 we can conclude, the value of drag coefficient decreases with an increase in the value of Reynolds number.

Table 7: Values of drag coefficient at different Reynolds number ranging from 1 to 100 for L/D=0.4

Re	**C_d**
1	21.01
1.5	14.71
2	11.57
4	6.74
8	4.09
10	3.53
20	2.38
30	1.996
40	1.81
50	1.7
60	1.62
70	1.57
80	1.52
90	1.49
100	1.46

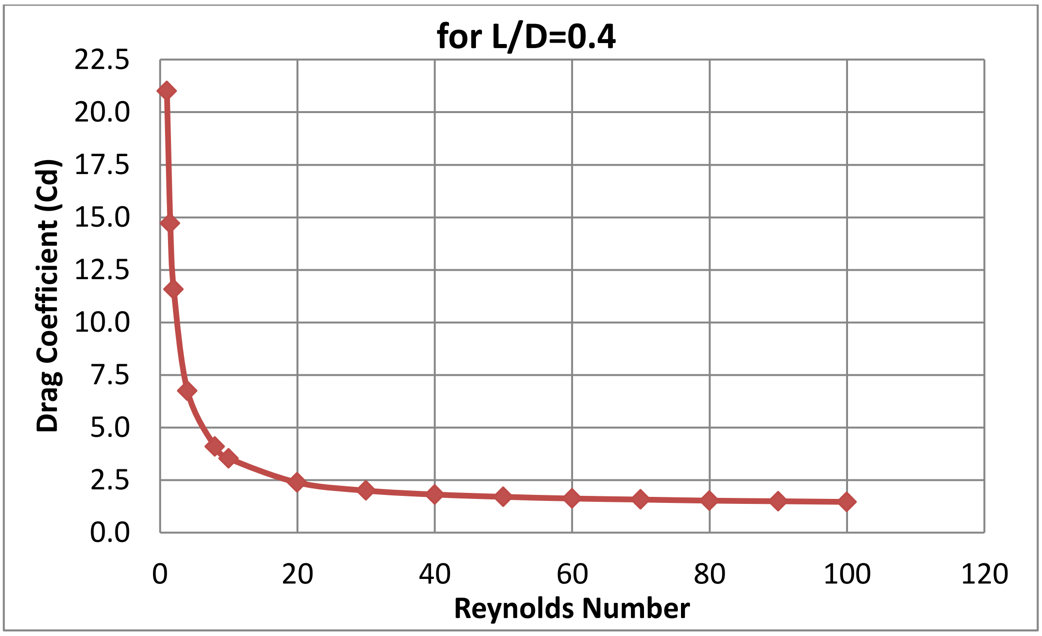

Figure 9: Variations of drag coefficient with Reynolds number al L/D =0.4

From the graph for L/D=0.4 we can conclude, the value of drag coefficient decreases with an increase in the value of Reynolds number.

Table 8: Values of drag coefficient at different Reynolds number ranging from 1 to 100 for L/D=0.5

Re	C_d
1	20.9
1.5	14.62
2	11.48
4	6.68
8	4.05
10	3.49
20	2.34
30	1.96
40	1.77
50	1.66
60	1.59
70	1.53
80	1.49
90	1.46
100	1.44

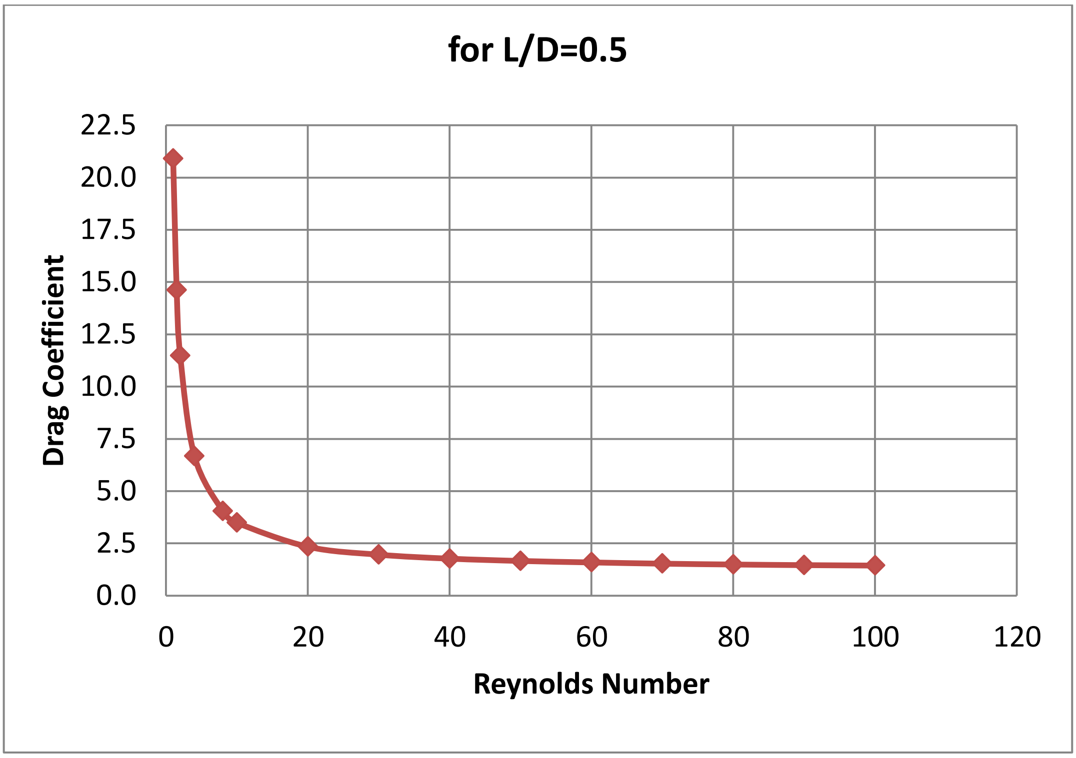

Figure 10: Variations of drag coefficient with Reynolds number al L/D =0.5

From the graph for L/D=0.5 we can conclude, the value of drag coefficient decreases with an increase in the value of Reynolds number.

Table 9: Values of drag coefficient at different Reynolds number ranging from 1 to 100 for L/D=0.6

Re	C_d
1	20.56
1.5	14.37
2	11.28
4	6.55
8	3.97
10	3.43
20	2.31
30	1.95
40	1.77
50	1.66
60	1.59
70	1.53
80	1.49
90	1.46
100	1.44

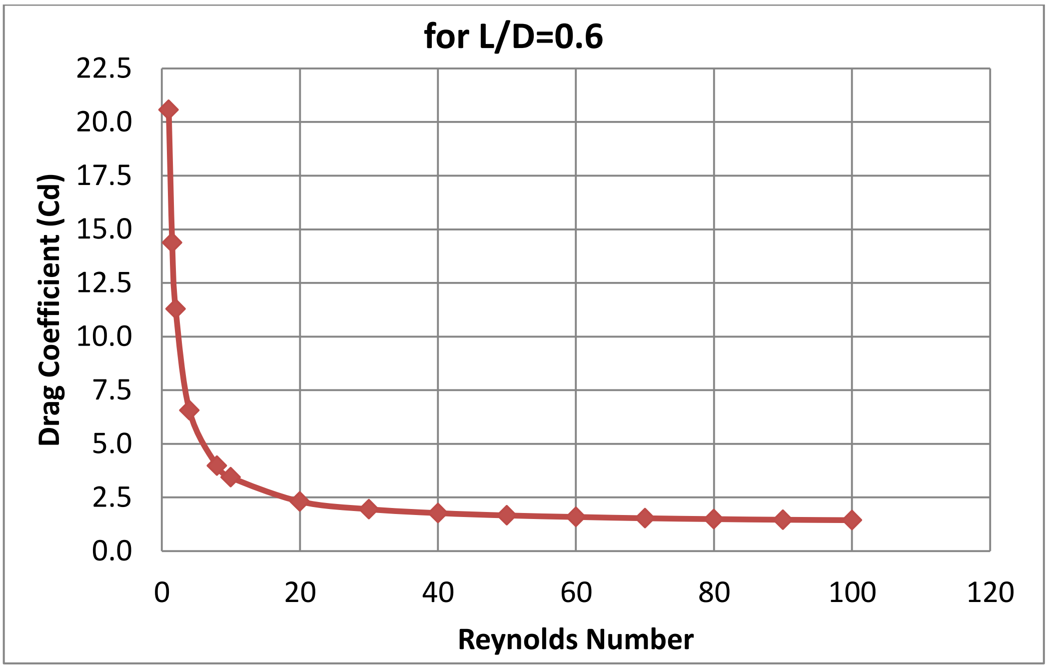

Table 11: Variations of drag coefficient with Reynolds number al L/D =0.6

From the graph for L/D=0.6 we can conclude, the value of drag coefficient decreases with an increase in the value of Reynolds number.

Table 10: Value of drag coefficient at different Reynolds number ranging from 1 to 100 for L/D=0.7

Re	**C_d**
1	20.84
1.5	14.56
2	11.43
4	6.62
8	3.99
10	3.44
20	2.31
30	1.94
40	1.76
50	1.65
60	1.54
70	1.52
80	1.48
90	1.45
100	1.42

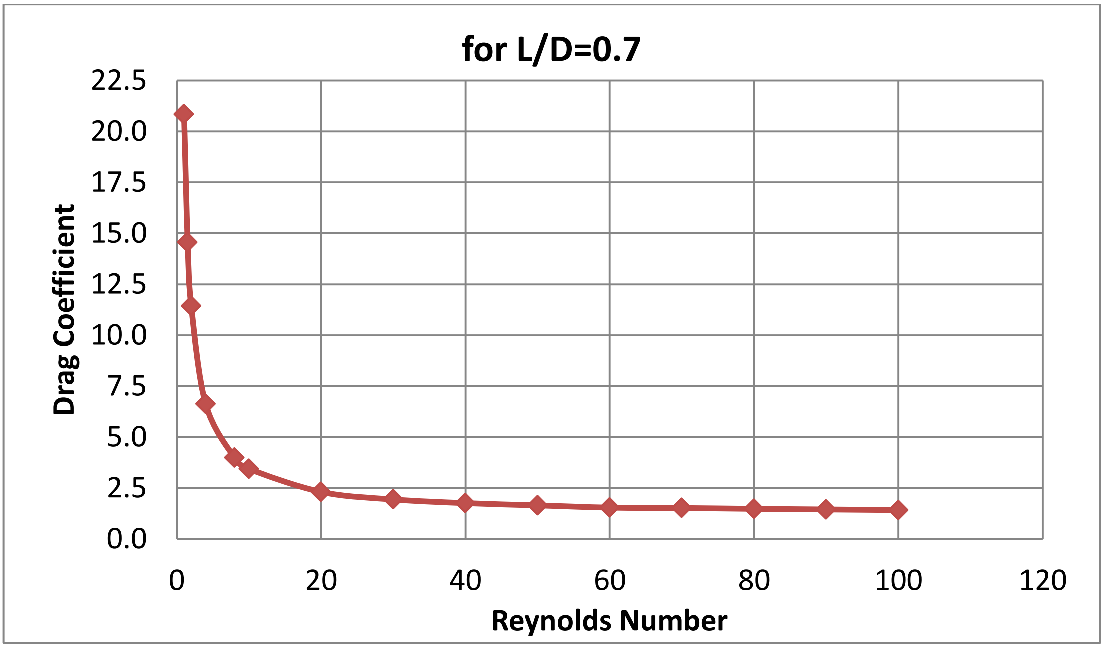

Figure 12: Variations of drag coefficient with Reynolds number al L/D =0.7

From the graph for L/D=0.7 we can conclude, the value of drag coefficient decreases with an increase in the value of Reynolds number.

Table 11: Values of drag coefficient at different Reynolds number ranging from 1 to 100 for L/D=0.8

Re	C_d
1	20.43
1.5	14.25
2	11.16
4	6.45
8	3.89
10	3.35
20	2.25
30	1.89
40	1.71
50	1.61
60	1.54
70	1.49
80	1.45
90	1.42
100	1.39

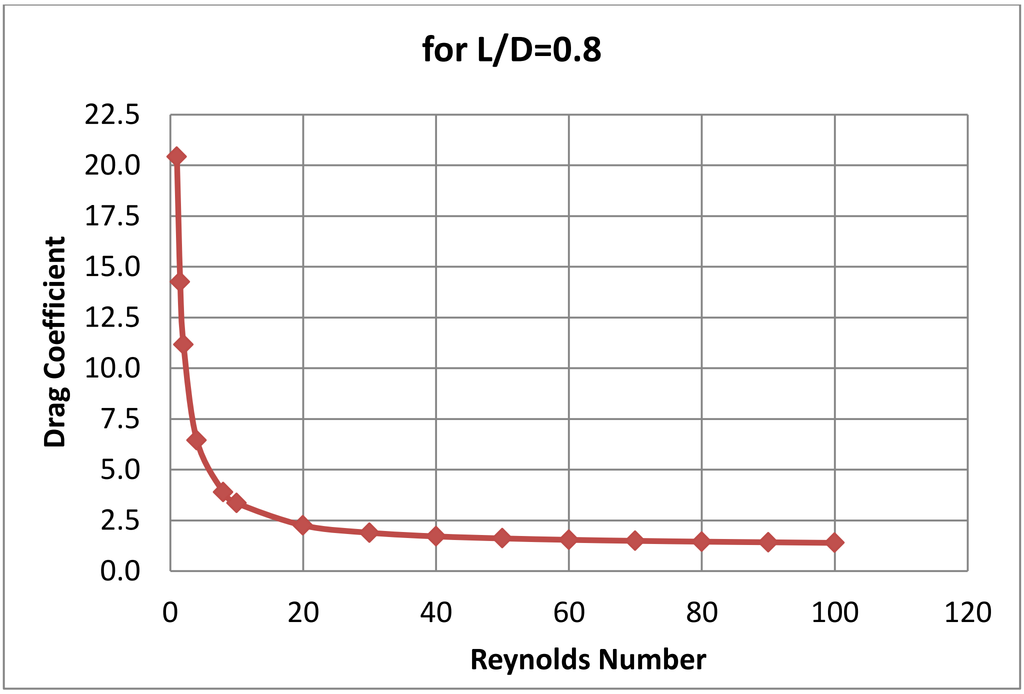

Figure 13: Variations of drag coefficient with Reynolds number al L/D =0.8

From the graph for L/D=0.8 we can conclude, the value of drag coefficient decreases with an increase in the value of Reynolds number.

Table 12: Values of drag coefficient at different Reynolds number ranging from 1 to 100 for L/D=0.9

Re	C_d
1	20.39
1.5	14.2
2	11.11
4	6.39
8	3.84
10	3.31
20	2.22
30	1.87
40	1.7
50	1.59
60	1.52
70	1.47
80	1.44
90	1.41
100	1.38

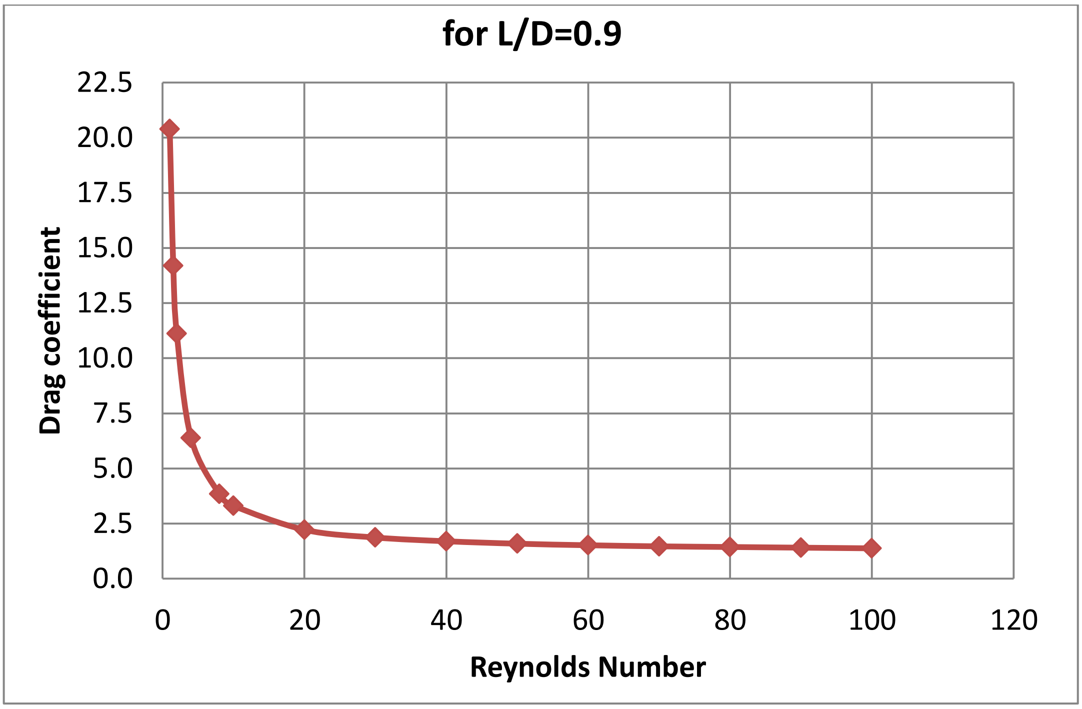

Figure 14: Variation of drag coefficient with Reynolds number al L/D =0.9

From the graph for L/D=0.9 we can conclude, the value of drag coefficient decreases with an increase in the value of Reynolds number.

Table 13: Values of drag coefficient at different Reynolds number ranging from 1 to 100 for L/D=1

Re	C_d
1	20.62
1.5	14.35
2	11.22
4	6.45
8	3.88
10	3.34
20	2.24
30	1.89
40	1.71
50	1.61
60	1.54
70	1.49
80	1.45
90	1.42
100	1.39

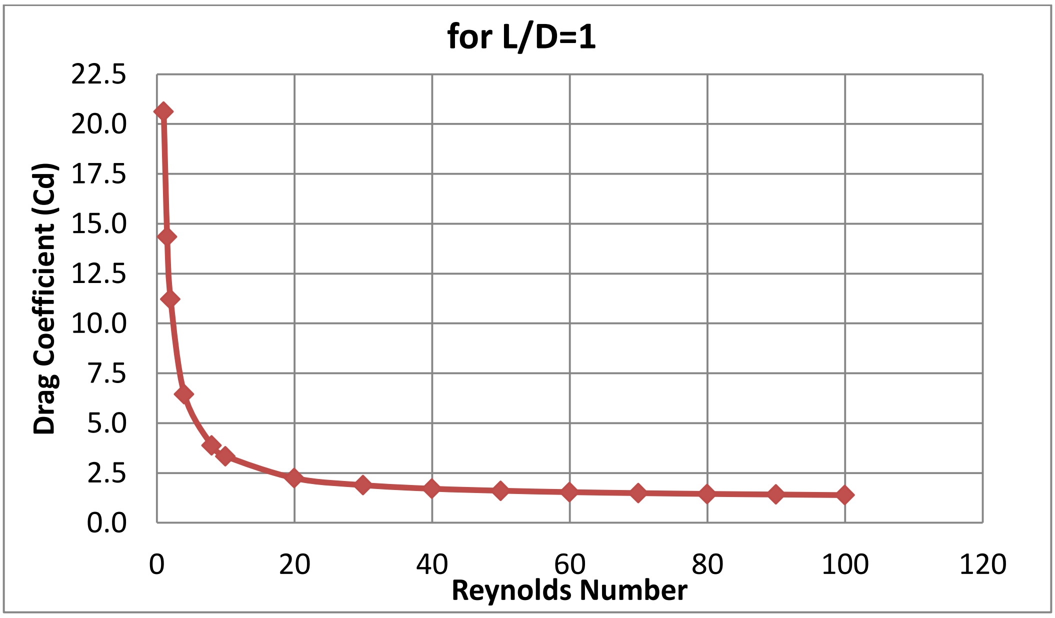

Figure 15: Variation of drag coefficient with Reynolds number al L/D =1

From the graph for L/D=0.1 we can conclude, the value of drag coefficient decreases with an increase in the value of Reynolds number.

So our results show that there is a general downward slope in case of a cylinder for all L/D ratios, plotting drag coefficient vs. Reynolds number. So in this case, drag coefficient depends on Reynolds number.

Table 14: Present values of Drag coefficient and comparison with Munshi et al. (1999) (compared with Cylinder for L/D=0.05)

Re	Present Value	Values by Munshi et al.	% Deviation
1	23.84	23.46	1.62
1.5	16.76	15.8	6.08
2	13.24	11.98	10.52
4	7.8	6.28	24.20
8	4.76	4.91	-3.05
10	4.16	4.14	0.48
20	2.77	2.58	7.36
30	2.31	2.02	14.36
40	2.09	1.74	20.11
50	1.95	1.55	25.81
60	1.86	1.47	26.53
70	1.8	1.44	25.00
80	1.74	1.35	28.89
90	1.7	1.33	27.82
100	1.67	1.27	31.50

The following graphs show the variation of drag coefficient values at a constant Reynolds number for different L/D ratios.

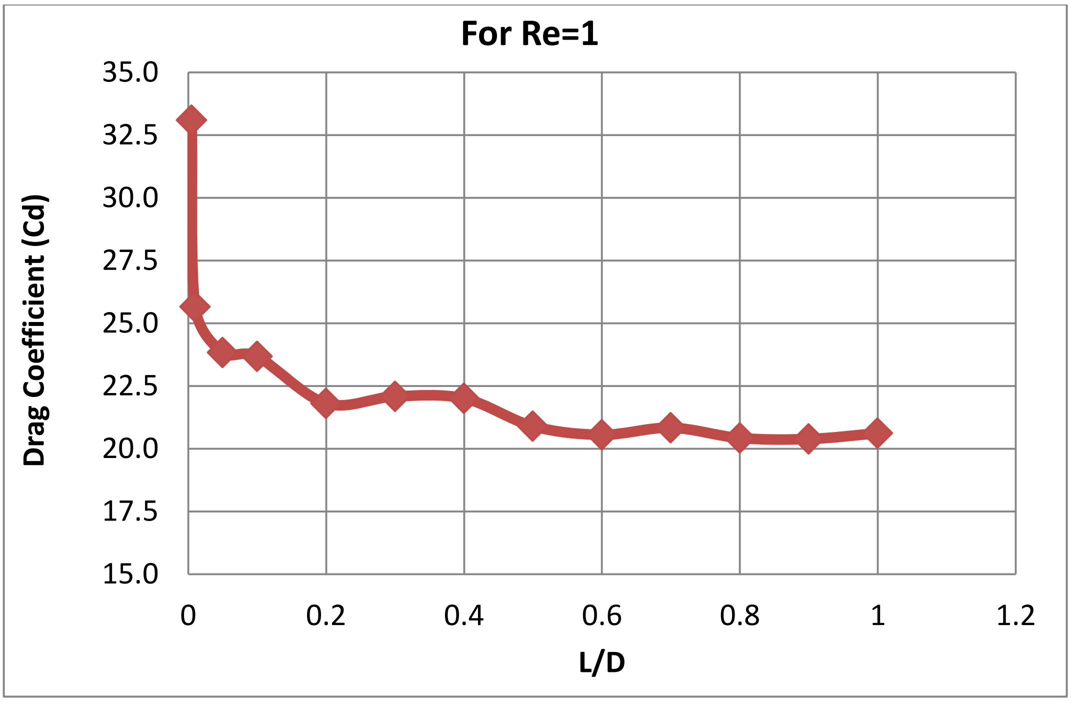

Figure 16: Variation of Drag Coefficient with L/D at Re=1

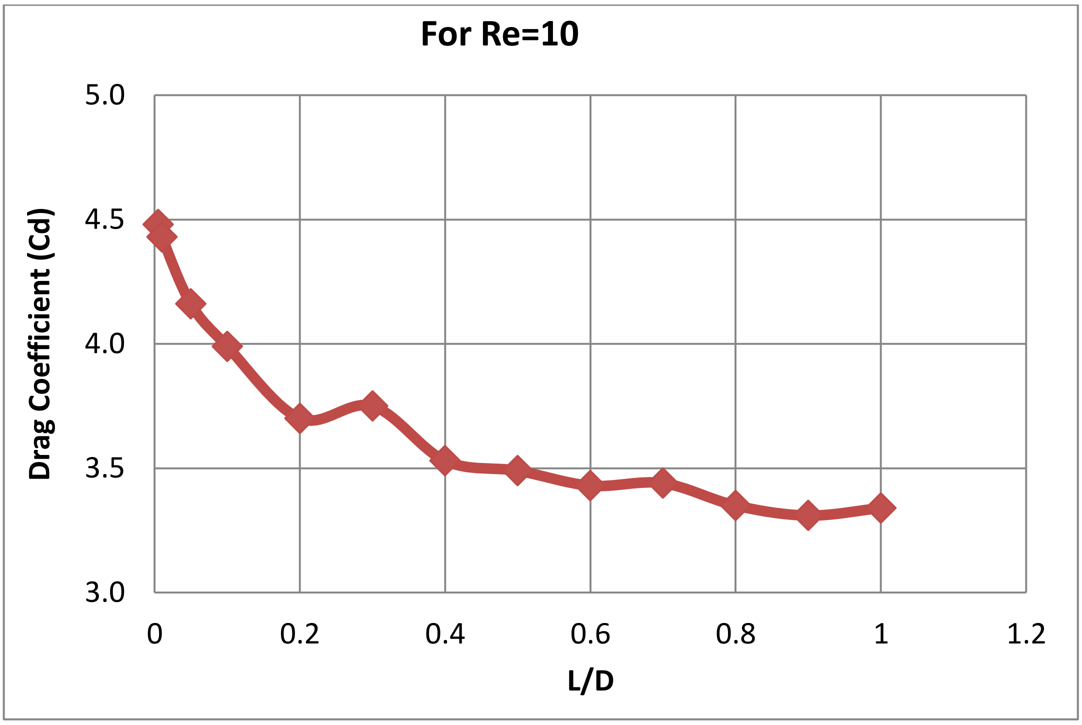

Figure 17: Variation of Drag Coefficient with L/D at Re=10

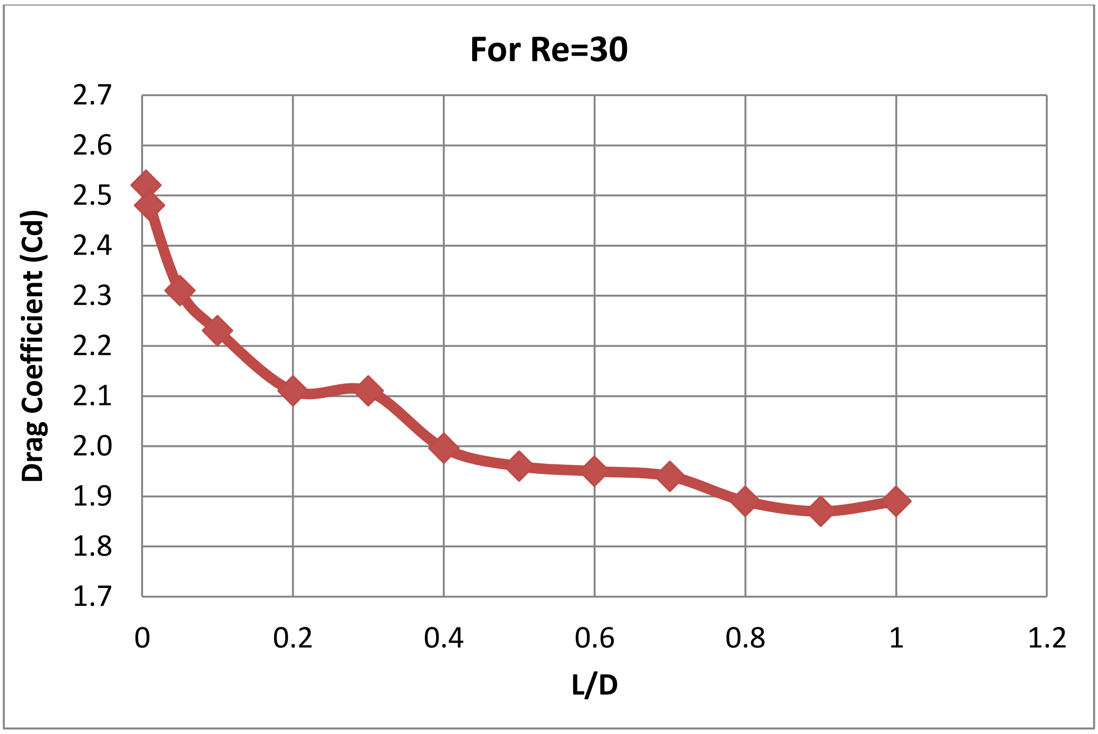

Figure 18: Variation of Drag Coefficient with L/D at Re=30

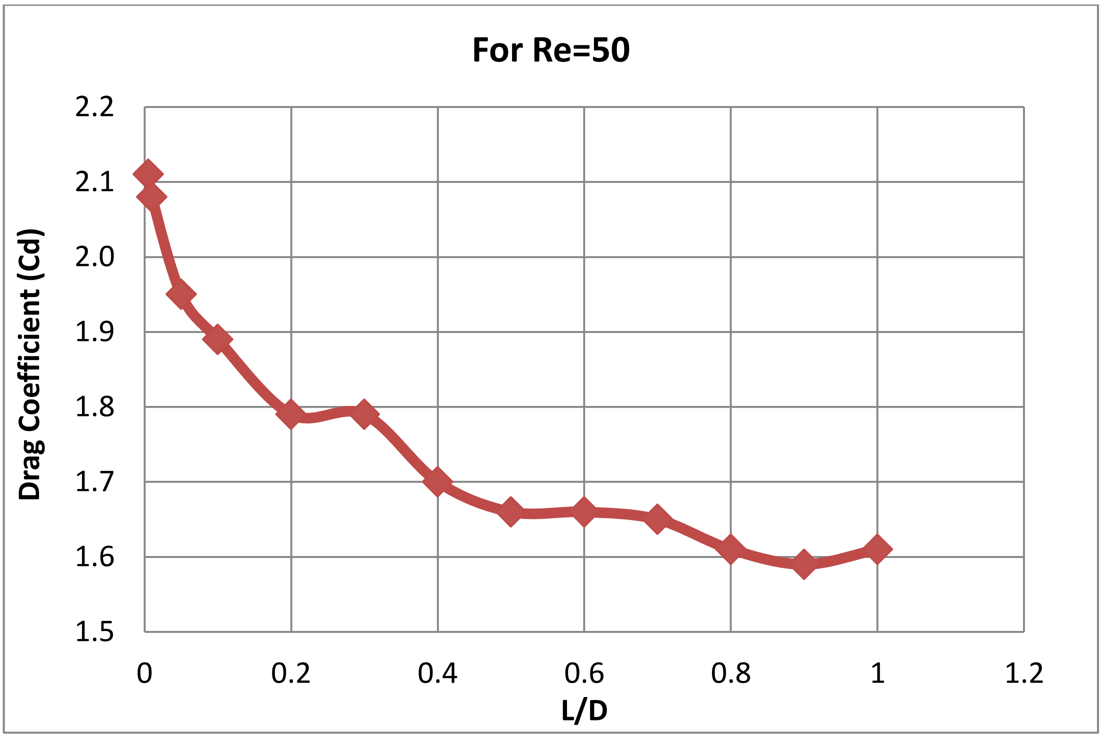

Figure 19: Variation of Drag Coefficient with L/D at Re=50

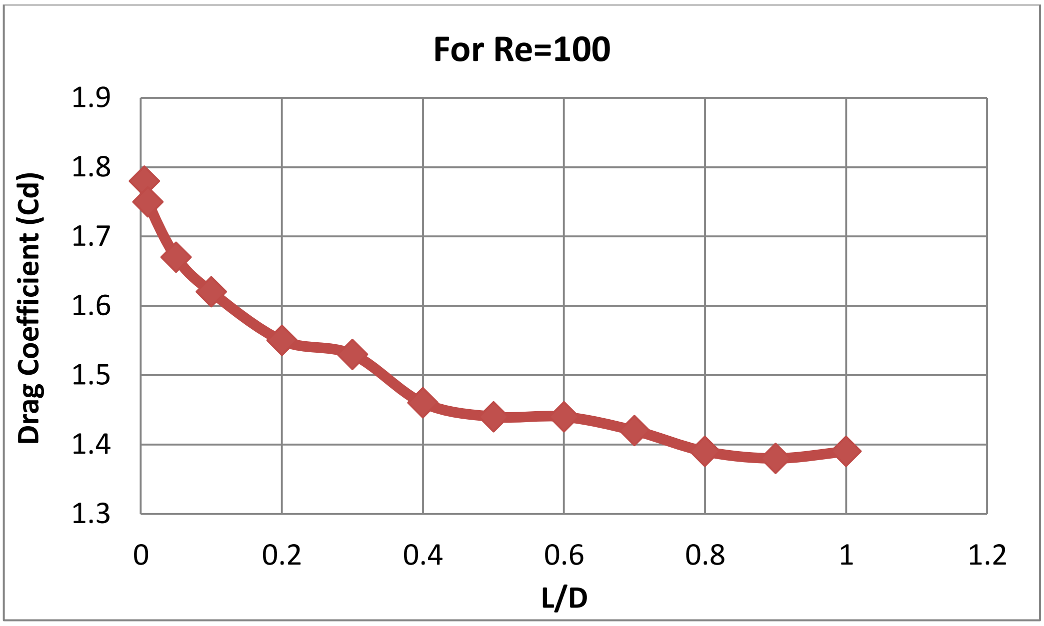

Figure 20: Variation of Drag Coefficient with L/D at Re=100

From these graphs it can be concluded that the value of drag coefficient decreases with increase in L/D ratio for a constant Reynolds number. If Reynolds number of any two cylinders is same, then they show the same hydrodynamic behaviour even they are of different sizes.

On plotting the values of drag coefficient at different Reynolds for L/D=1 of cylinder with that of a sphere we get the following graph. The values of drag coefficient of a sphere are calculated using the correlation given by *Morrison F.A., Department of Chemical Engineering, Michigan Technological University.*

$$Cd = \frac{24}{Re} + \frac{2.6\left(\frac{Re}{5.0}\right)}{1+\left(\frac{Re}{5.0}\right)^{1.52}} + \frac{0.411\left(\frac{Re}{263000}\right)^{-7.94}}{1+\left(\frac{Re}{263000}\right)^{-8.00}} + \frac{Re^{0.80}}{461000}$$

C_d values are calculated from the above formula as in Table 15.

Table 15: Values of Drag Coefficient for Re from 1 to 100 for a Sphere:

Re	C_d
1	24.67
1.5	16.87
2	13.04
4	7.43
8	4.59
10	3.97
20	2.56
30	1.99
40	1.69
50	1.49
60	1.35
70	1.24
80	1.16
90	1.09
100	1.04

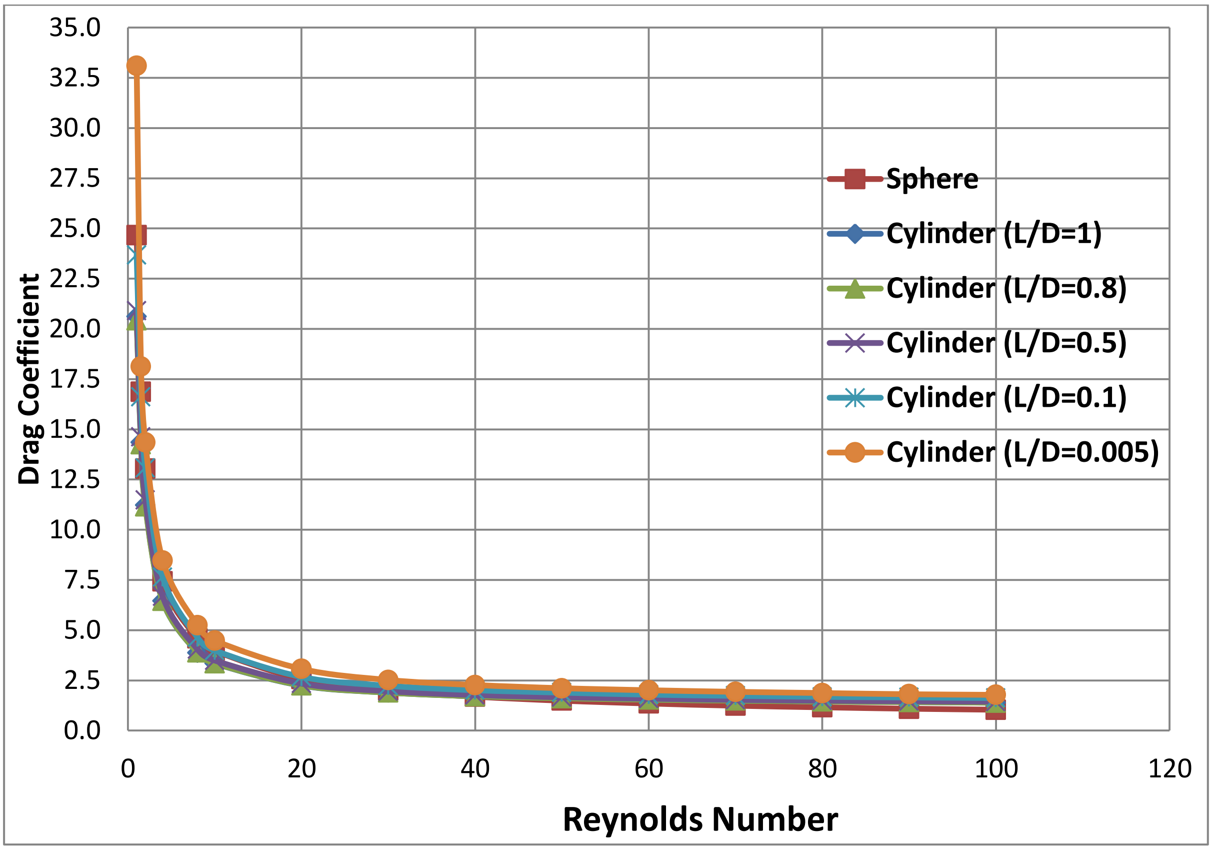

Figure 21: Re vs. Cd for Cylinder with L/D=1 and that of the Sphere

From figure 21, we can conclude that values of drag coefficient of a cylinder almost converges with that of a sphere as the sphericity of ideal cylinder, that is L=D=1, almost tends to 1. For Reynolds number less than 10, the drag is due to frictional drag. At about Reynolds number equal to 10, separation starts occurring on the rear of the body with vortex shedding starting at about Reynolds number of 90. The region of separation increases with increase in Reynolds number. The drag coefficient continues to decrease with an increase in Reynolds number.

The contour plots of L/D =0.01 at Re=1:

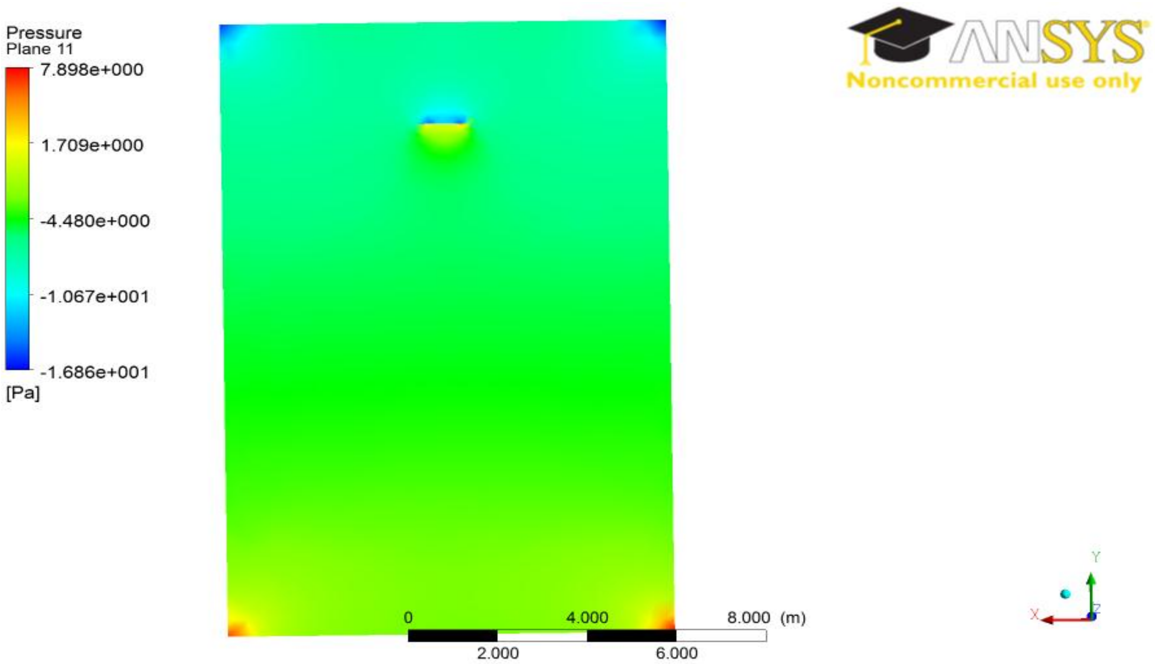

Figure 22: Pressure Contour for L/D =0.01 at Re=1

From the plot, the pressure of the inlet fluid is almost constant. The pressure just above the top surface of the cylinder is low and at the bottom face is comparatively higher. There exists pressure gradient in the bottom face of the cylinder up to a certain region and then increases.

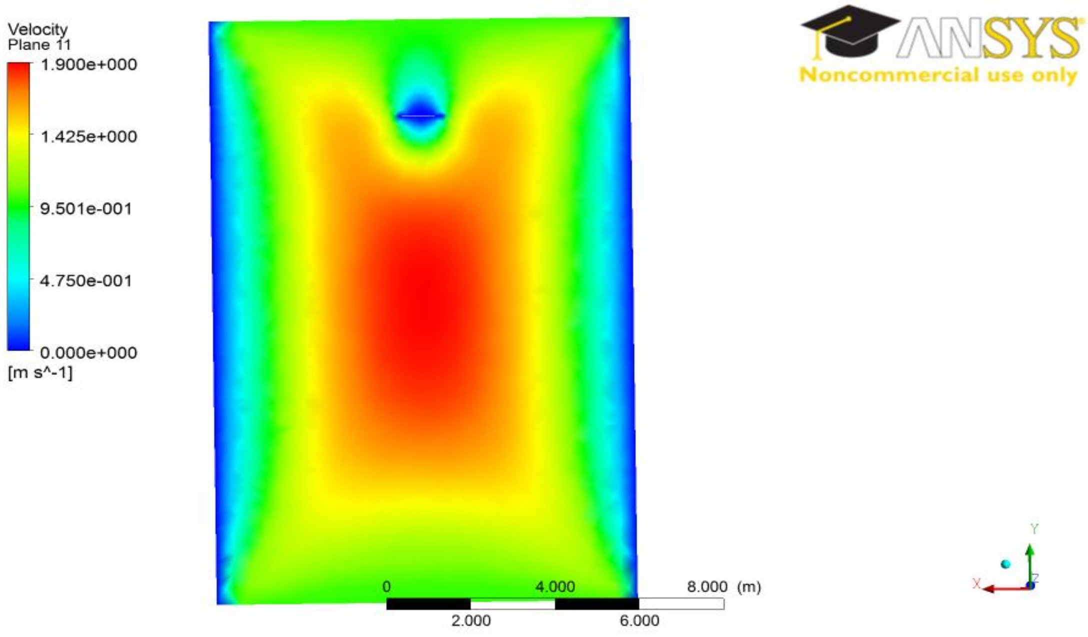

Figure 23: Velocity Contour for L/D =0.01 at Re=1

From the velocity contours, we find that velocity of the entering fluid is constant. The velocity of the fluid around the surface of the cylinder and up to some region is zero and gradually increases. The velocity of the walls of the flow domain is zero, which shows that the walls have zero or negligible effect on the cylinder.

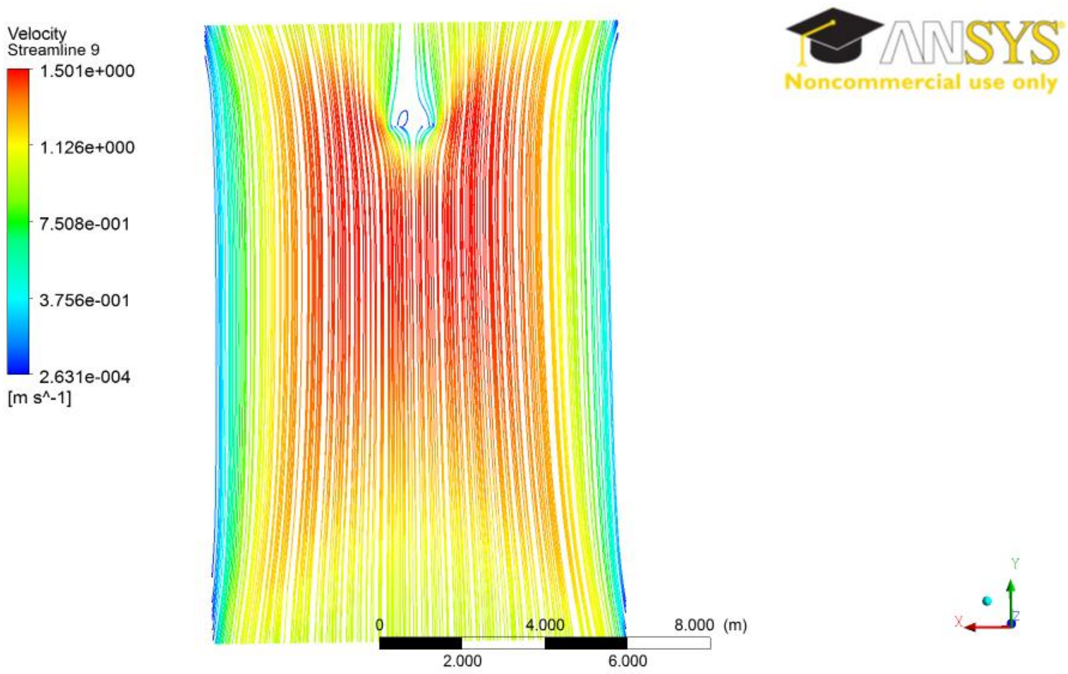

Figure 24: Velocity Streamline Contour for L/D =0.01 at Re=1

The velocity streamline contours shows symmetry.

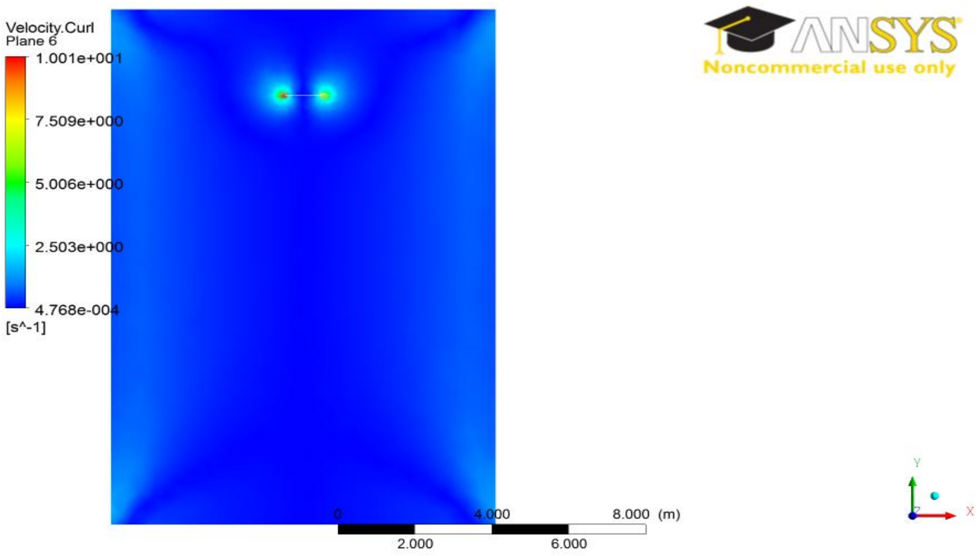

Figure 25: Vorticity Streamline Contour for L/D =0.01 at Re=1

There are steep gradients of vorticity around the walls of the cylinder. It means the circulation of fluid id more over these places.

The contour plots of L/D =0.01 at Re=10:

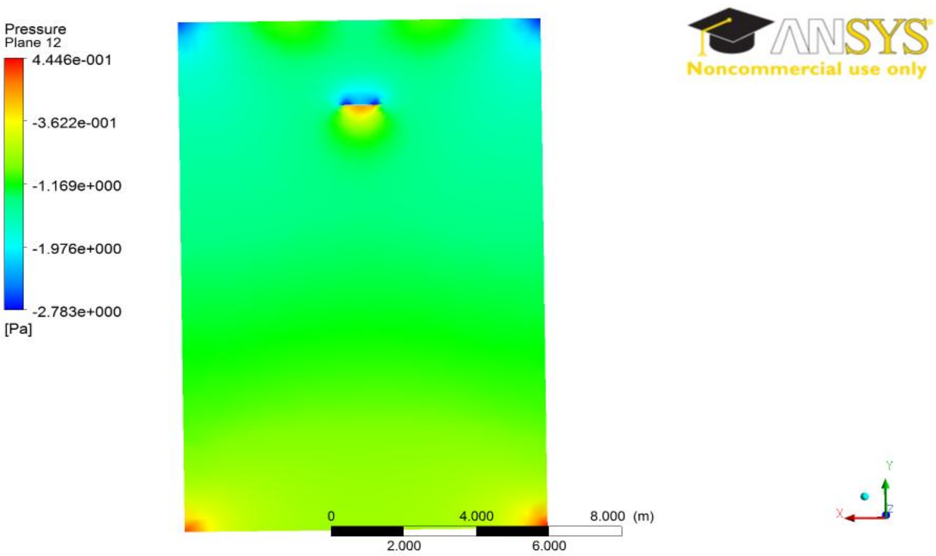

Figure 26: Pressure Contour for L/D =0.01 at Re=10

The pressure contours shows steep gradients in region near the bottom of the cylinder. Then in the downstream region pressure remains uniformly constant till certain distance and then increases. In the top face of the cylinder there is also variation in pressure.

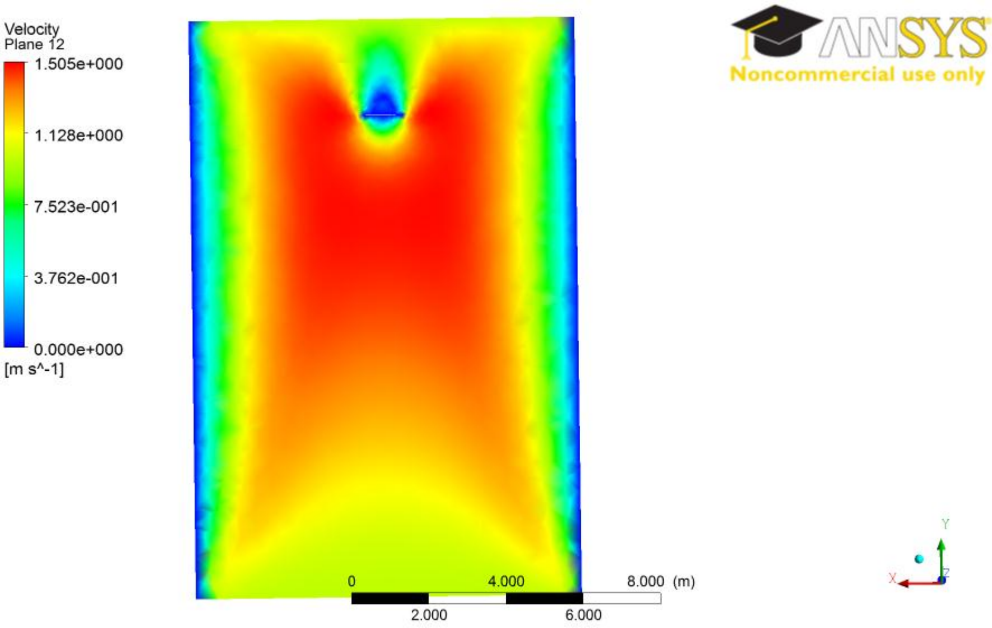

Figure 27: Velocity Contour for L/D =0.01 at Re=10

The velocity contours show there is variation in velocity both in top and bottom face of the cylinder. But there are steep gradients in the bottom face of the cylinder. The velocity of the walls of flow domain is zero, which shows that the walls have zero or negligible effect on the cylinder.

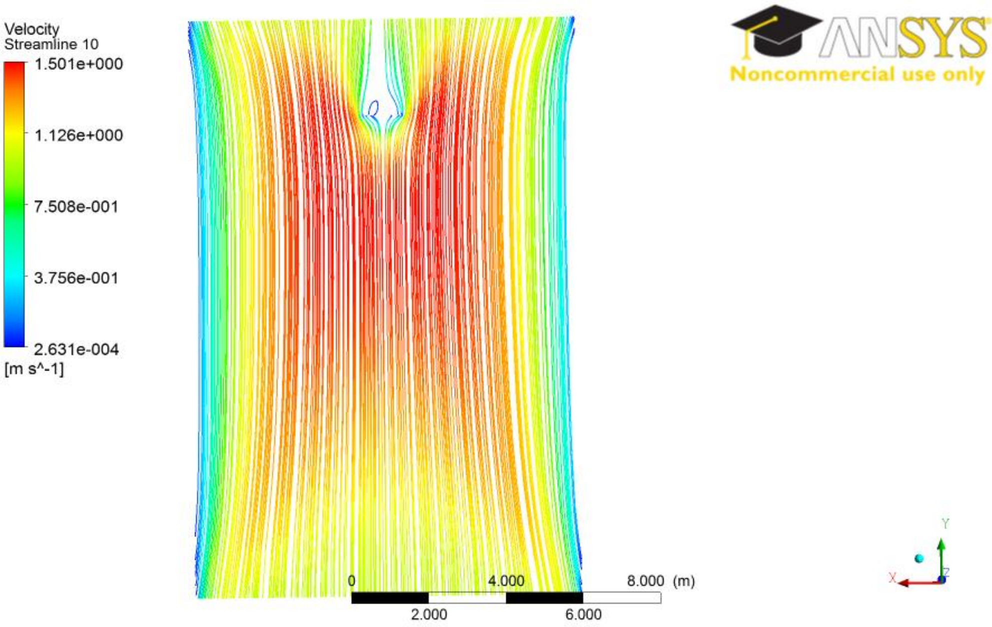

Figure 28: Velocity Streamline Contour for L/D =0.01 at Re=10

Velocity streamlines contour showing symmetry on both sides of the cylinder in the plane.

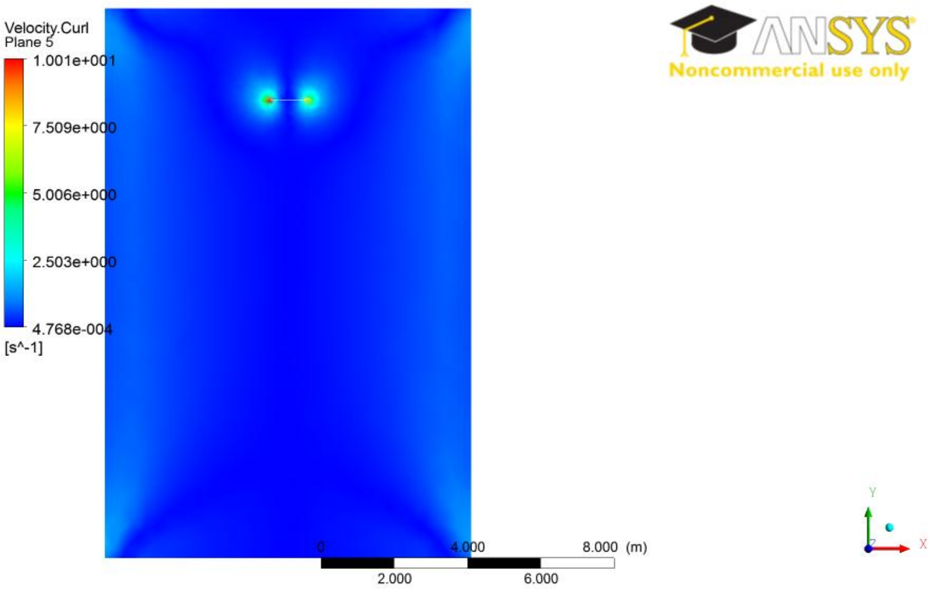

Figure 29: Vorticity Streamline Contour for L/D =0.01 at Re=10

There are steep gradients of vorticity around the walls of the cylinder. It means the circulation of fluid id more over these places.

The contour plots of L/D =0.01 at Re=100:

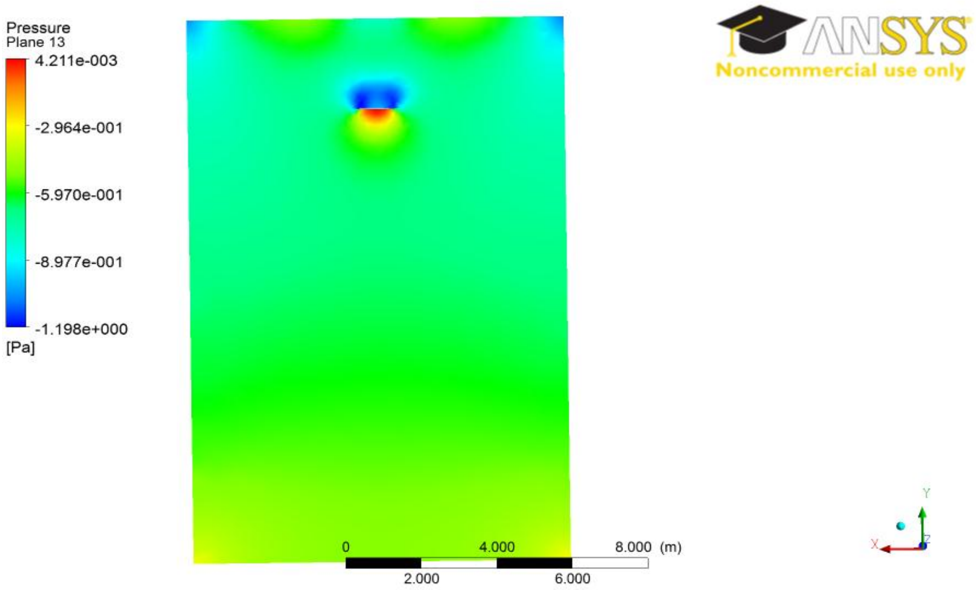

Figure 30: Pressure Contour for L/D =0.01 at Re=100

From the pressure contour we see that the pressure is almost constant around some area of the top face of the cylinder and above it, pressure is higher. And in the bottom face of the cylinder there is steep gradients in pressure. Then the pressure remains uniformly constant till some region and increases.

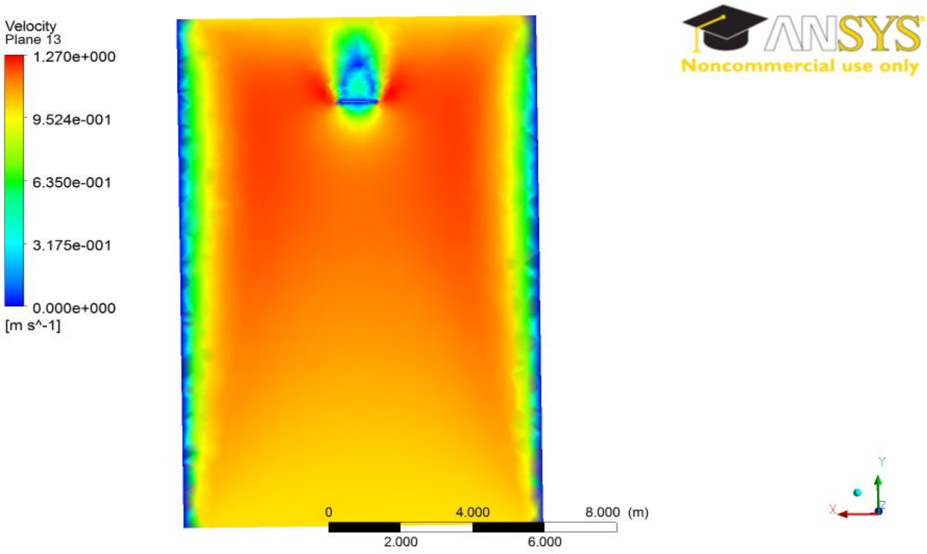

Figure 31: Velocity Contour for L/D =0.01 at Re=100

Velocity of fluid around the cylinder is zero. There is variation in velocity around the top face of the cylinder which extends up to large region in comparison to the bottom face. In bottom face also there is variation in velocity, the velocity gradually increases downstream. The velocity of the walls of the flow domain is zero, which shows that the walls have zero or negligible effect on the cylinder. Also in the lower most region of downstream flow, velocity remains constant.

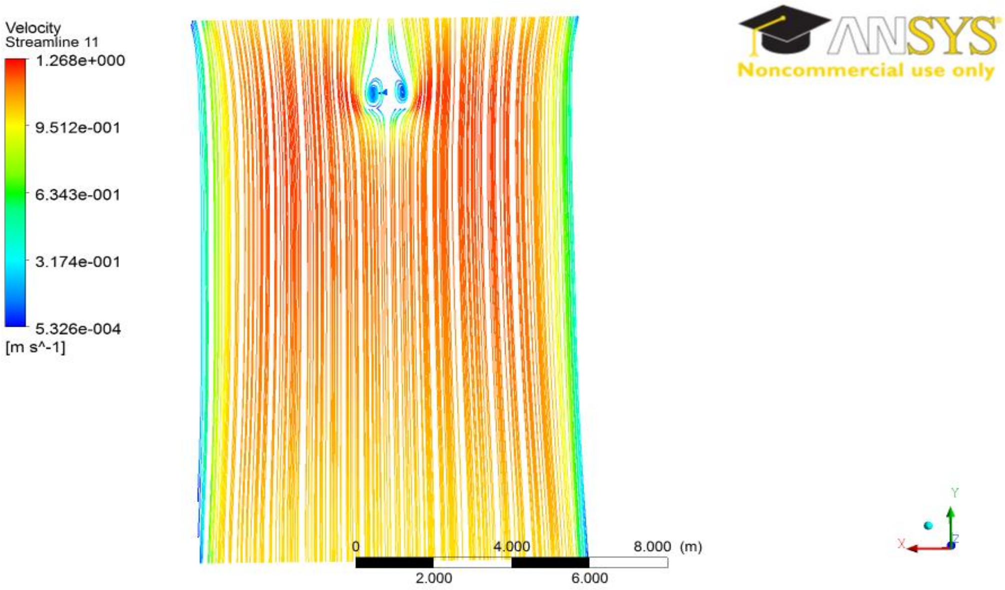

Figure 32: Velocity Streamline Contour for L/D =0.01 at Re=100

Streamlines show symmetry of the flow.

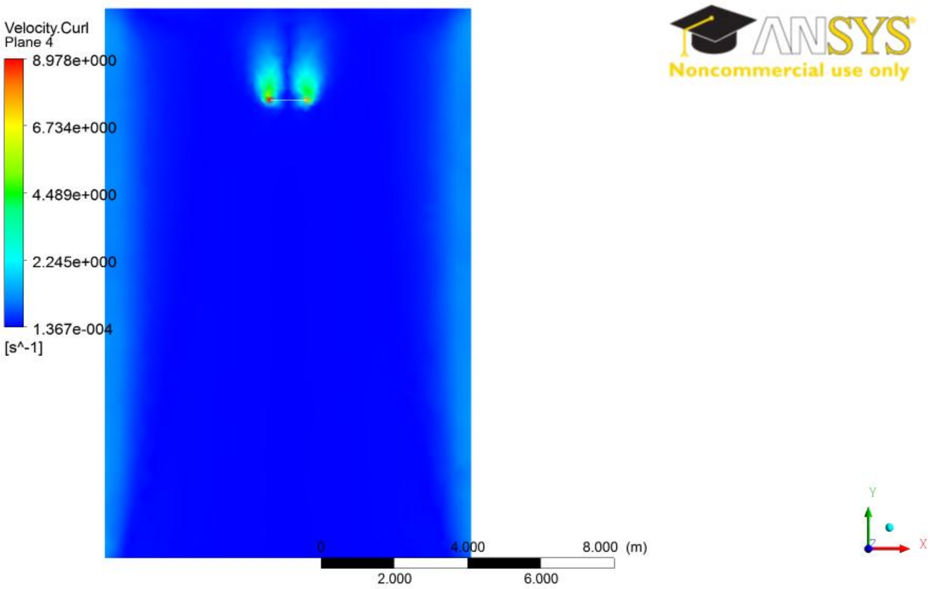

Figure 33: Vorticity Streamline Contour for L/D =0.01 at Re=100

There are steep gradients of vorticity around the walls of the cylinder. It means the circulation of fluid id more over these places. And the vorticity gradients in the upstream extends to greater region.

Following are the contour plots for L/D=0.05 at Re=1

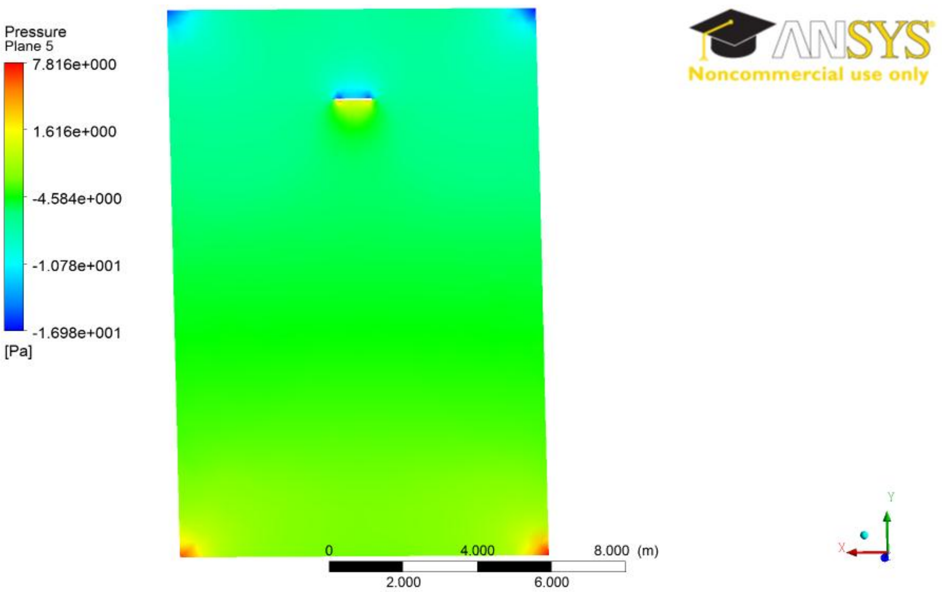

Figure 34: Pressure Contour for L/D=0.05 at Re=1

From the plot, the pressure of the inlet fluid is constant and gradually decreases as it passes over the cylinder. And the pressure just above the top surface of the cylinder is lower. At the bottom face there is variations in the pressure.

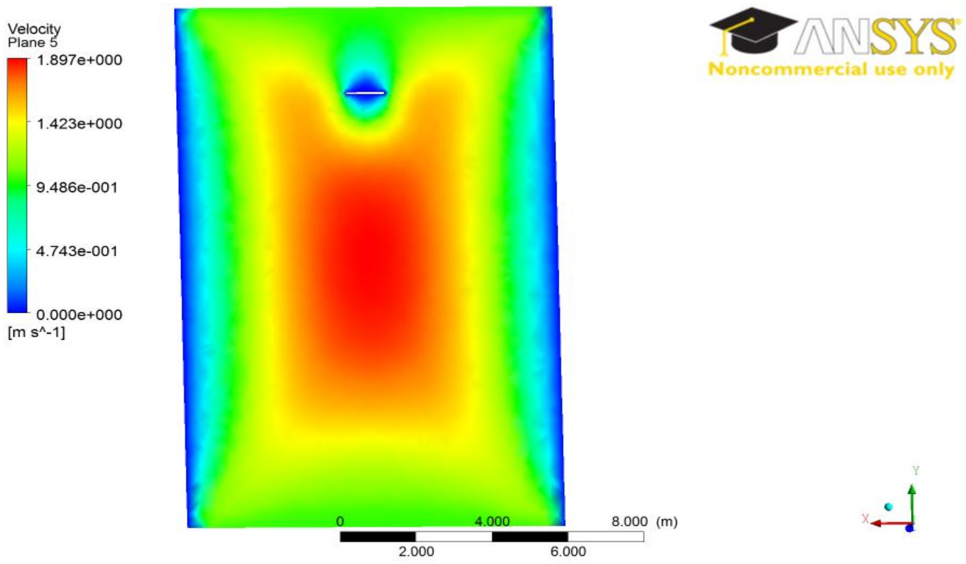

Figure 35: Velocity Contour for L/D=0.05 at Re=1

From the velocity contours, we find that velocity of the entering fluid is constant. The velocity of the fluid around the surface of the cylinder up to some region is zero. Then there is gradient in velocity for both the top and bottom region of the cylinder.

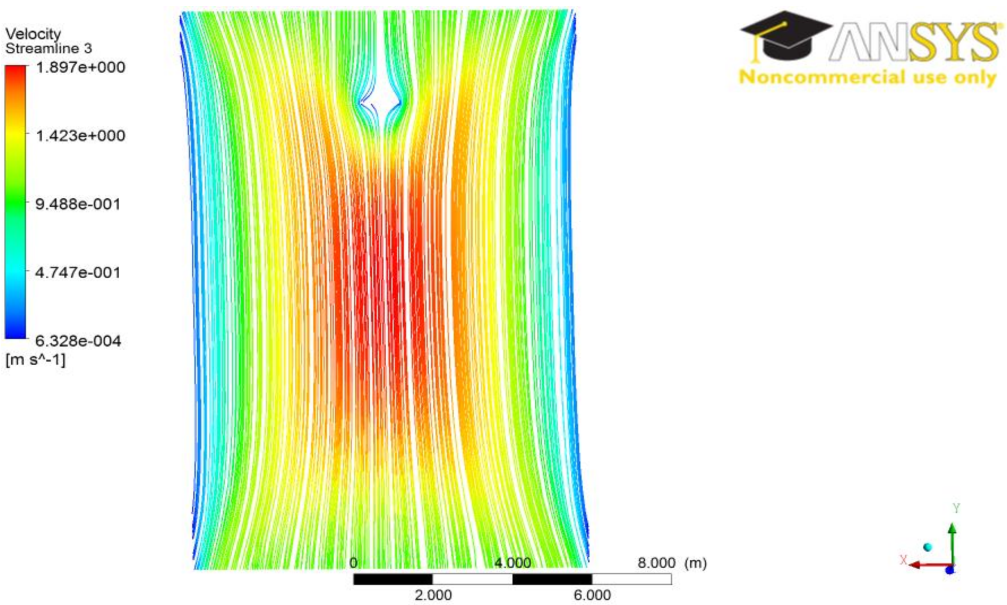

Figure 36: Velocity Streamline Contour for L/D=0.05 at Re=1

The above is the contours of velocity streamlines. It shows symmetry of the flow.

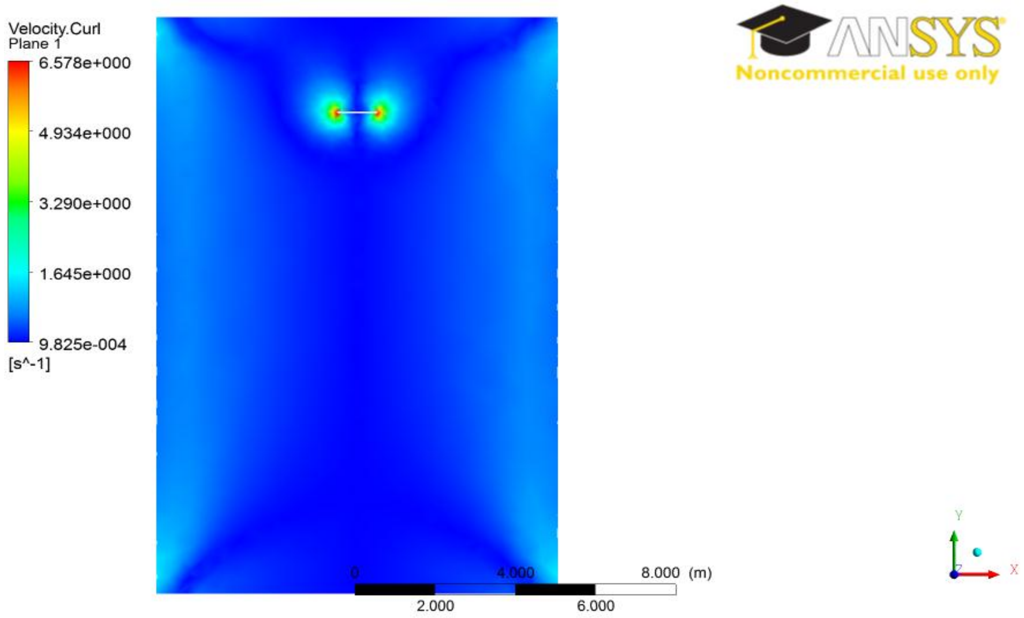

Figure 37: Vorticity Streamline Contour for L/D=0.05 at Re=1

There are steep gradients of vorticity around the walls of the cylinder. It means the circulation of fluid id more over these places.

Following are the contour plots for L/D=0.05 at Re=10:

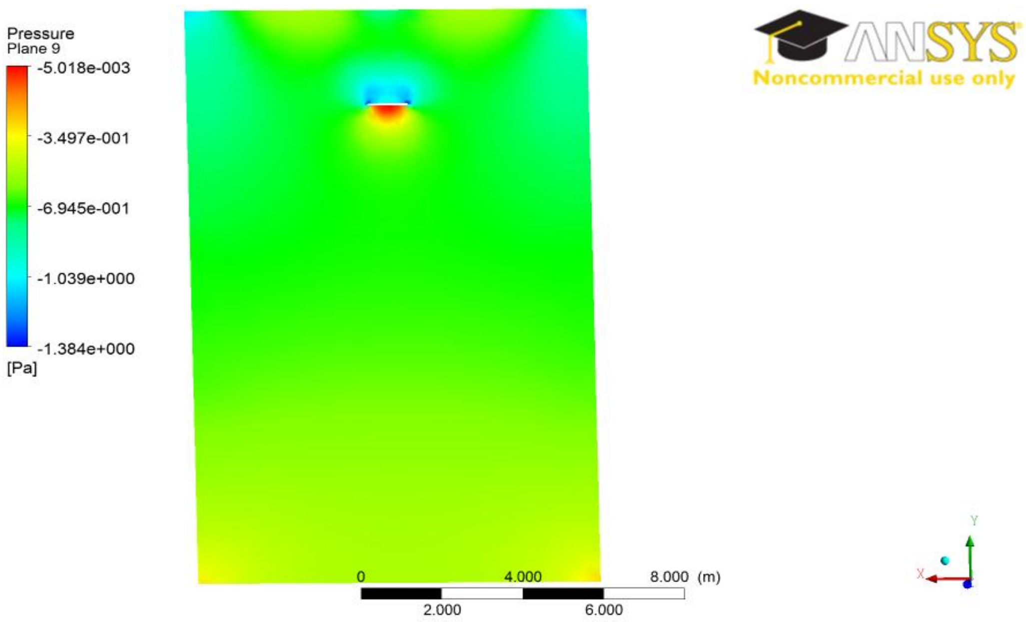

Figure 38: Pressure Contour for L/D=0.05 at Re=10

There exists some variation in pressure around top face of the cylinder. And steep variations of pressure exist around some region in the bottom face of the cylinder and then the pressure remains constant.

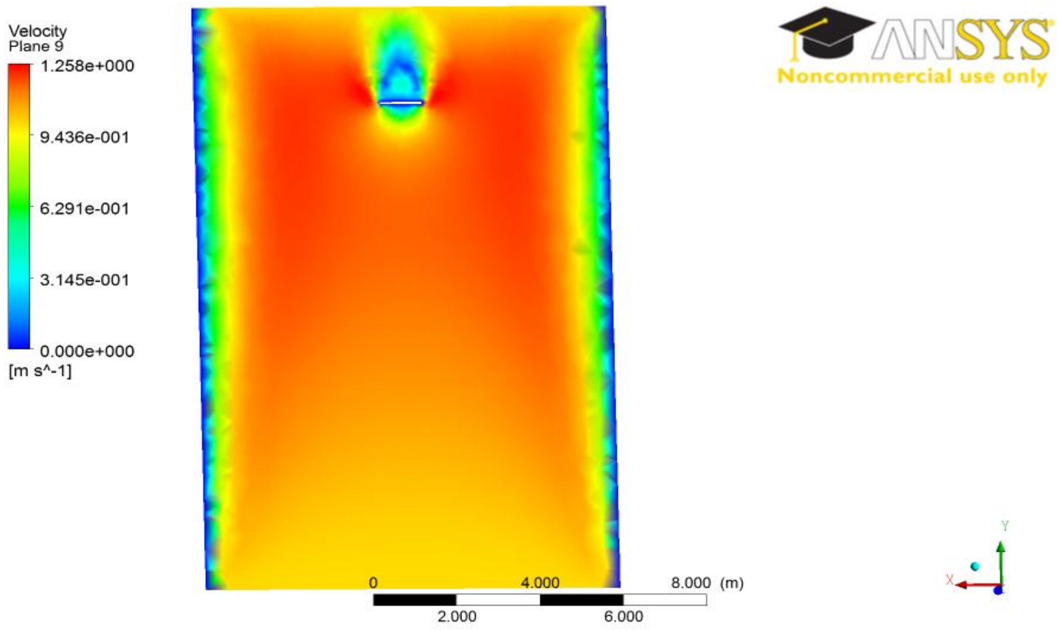

Figure 39: Velocity Contour for L/D=0.05 at Re=10

The velocity is zero around a small region of the cylinder as can be seen from the contours of the plane. And then again up to some region the velocity remains constant, and then there are variations in velocity distribution.

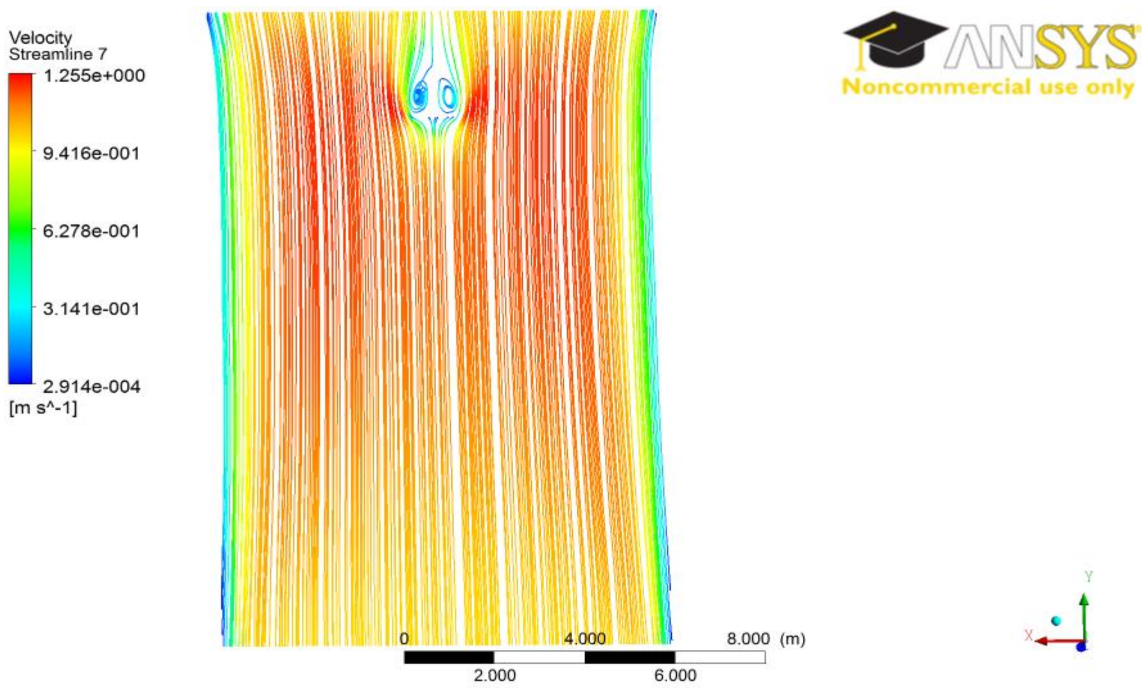

Figure 40: Velocity Streamline Contour for L/D=0.05 at Re=10

Streamlines shows symmetry of flow around the cylinder in the flow domain.

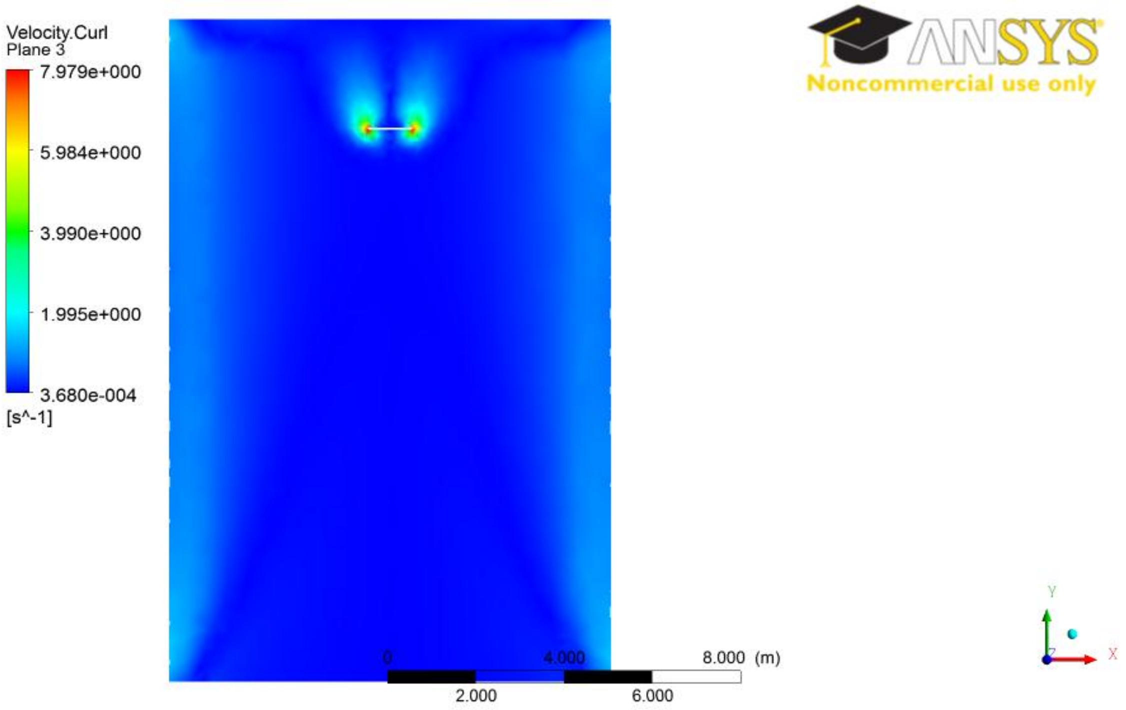

Figure 41: Vorticity Contour for L/D=0.05 at Re=10

There are steep gradients of vorticity around the walls of the cylinder. It means the circulation of fluid id more over these places. And the vorticity gradients in the upstream extends to greater region.

Following are the contour plots for L/D=0.05 at Re=100

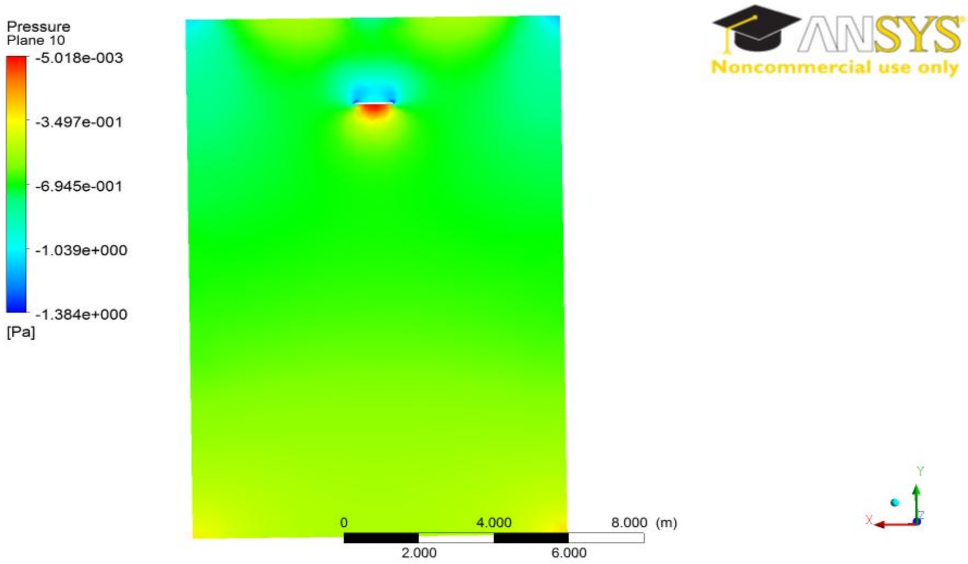

Figure 42: Pressure Contour for L/D=0.05 at Re=100

From the pressure contour we see that the pressure is almost constant around some area of the top face of the cylinder. And in the bottom face of the cylinder there is steep gradients in pressure up to some region of bottom face. Then the pressure remains constant.

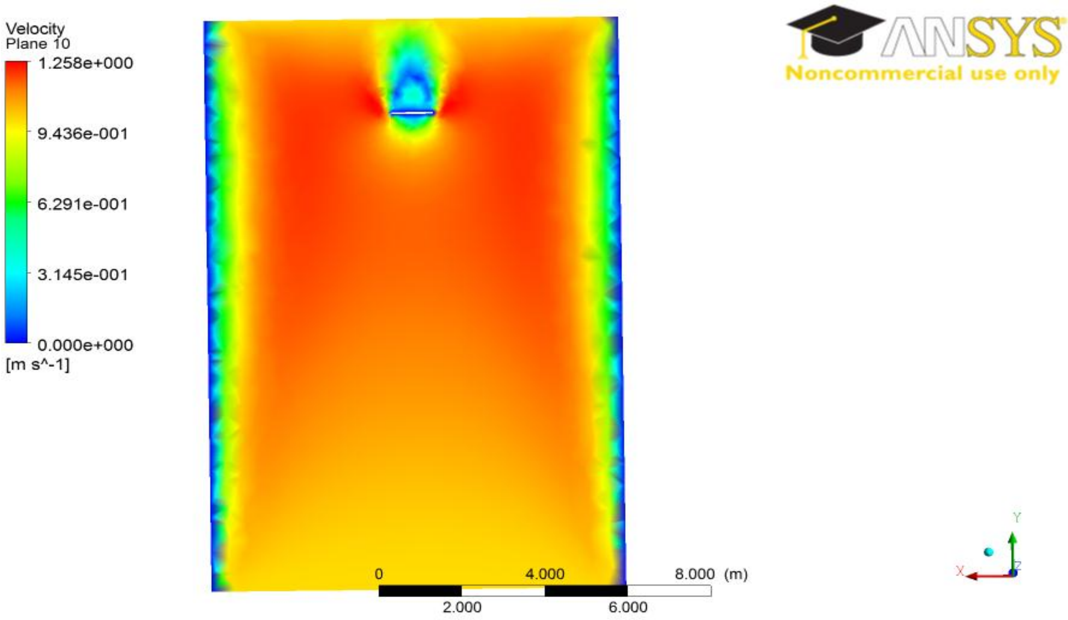

Figure 43: Velocity Contour for L/D=0.05 at Re=100

Velocity is zero, as can be seen from the contour plot, up to some region surrounding the cylinder. There is variation in velocity around the top face of the cylinder which extends up to large area in comparison to the bottom face. In bottom face also there is variation in velocity; the velocity gradually increases downstream and then remains constant. Velocity at the walls of the flow domain is zero, which shows the walls have negligible or no effect on the flow over the cylinder. And gradually the velocity increases away from the wall.

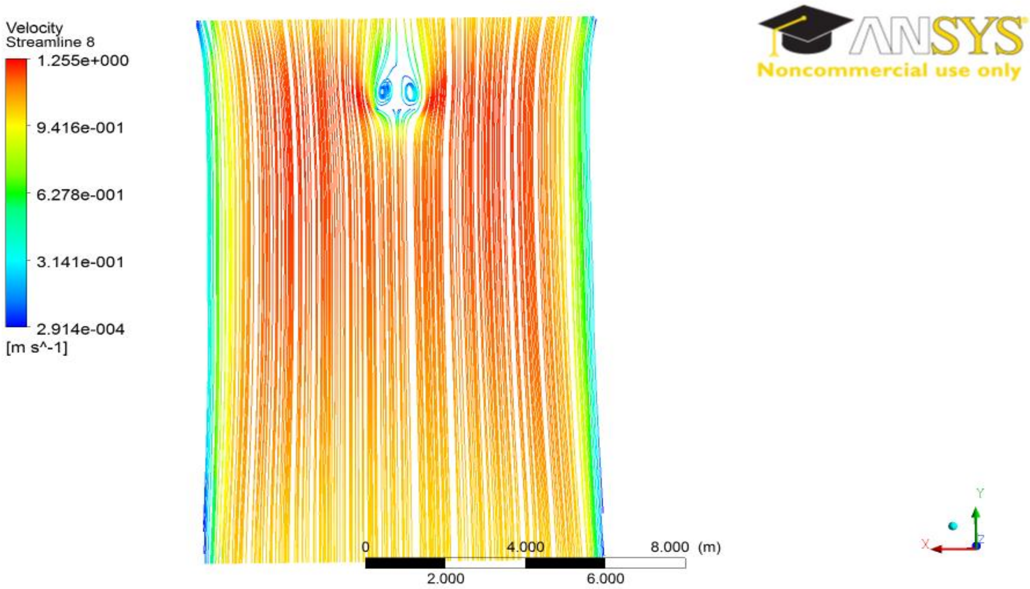

Figure 44: Velocity Streamline Contour for L/D=0.05 at Re=100

Streamlines shows symmetry of flow around the cylinder in the flow domain.

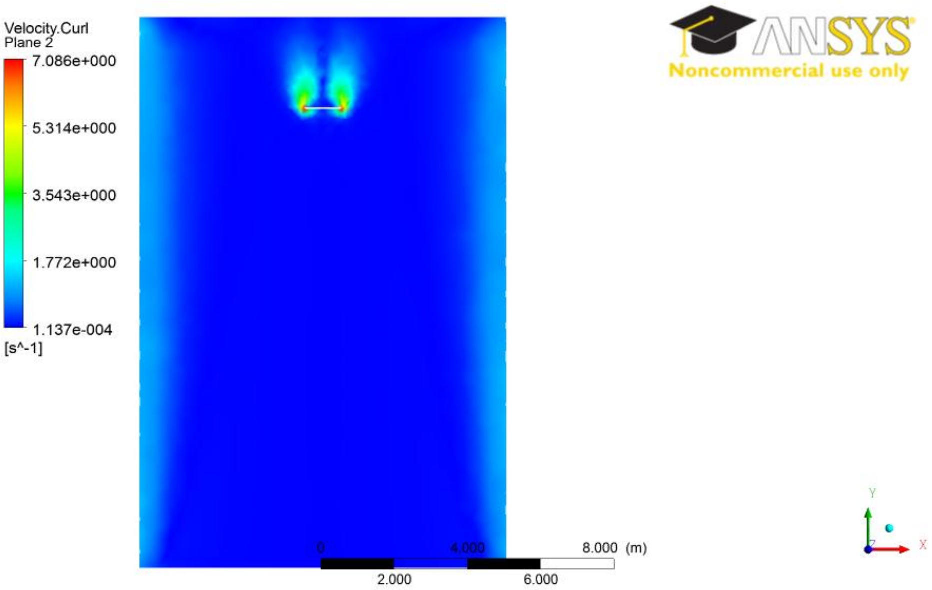

Figure 45: Vorticity Contour for L/D=0.05 at Re=100

There are steep gradients of vorticity around the walls of the cylinder. It means the circulation of fluid id more over these places. And the vorticity gradients in the upstream extends to greater region.

Following are the contour plots for L/D=0.1 at Re=1

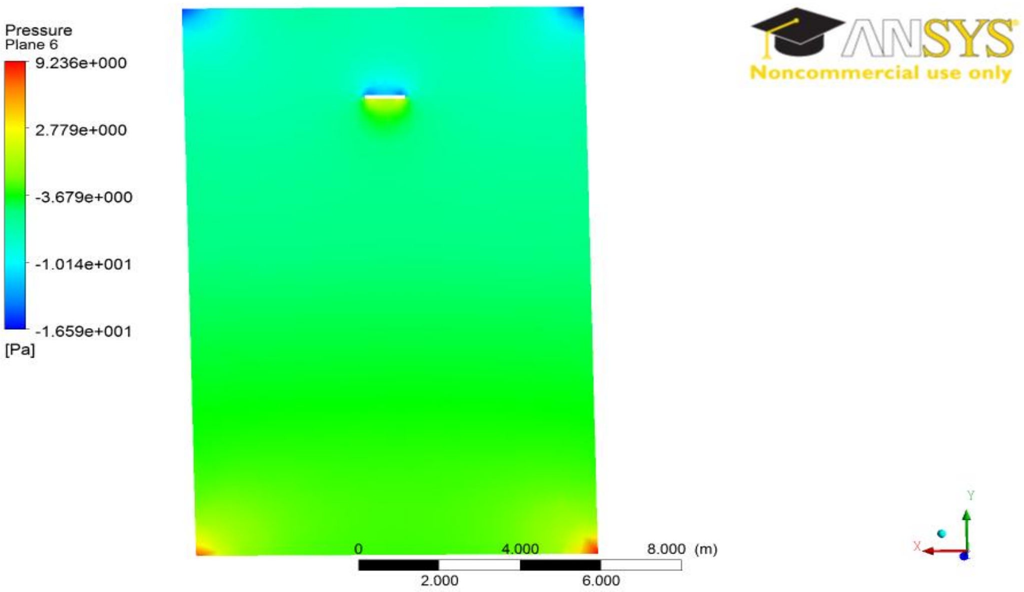

Figure 46: Pressure Contour for L/D=0.1 at Re=1

From the plot, the pressure of the inlet fluid is constant and is very low over the top face of the cylinder. At the bottom face there is some variations in the pressure. The pressure in the bottom face of the cylinder is more than that at the top face.

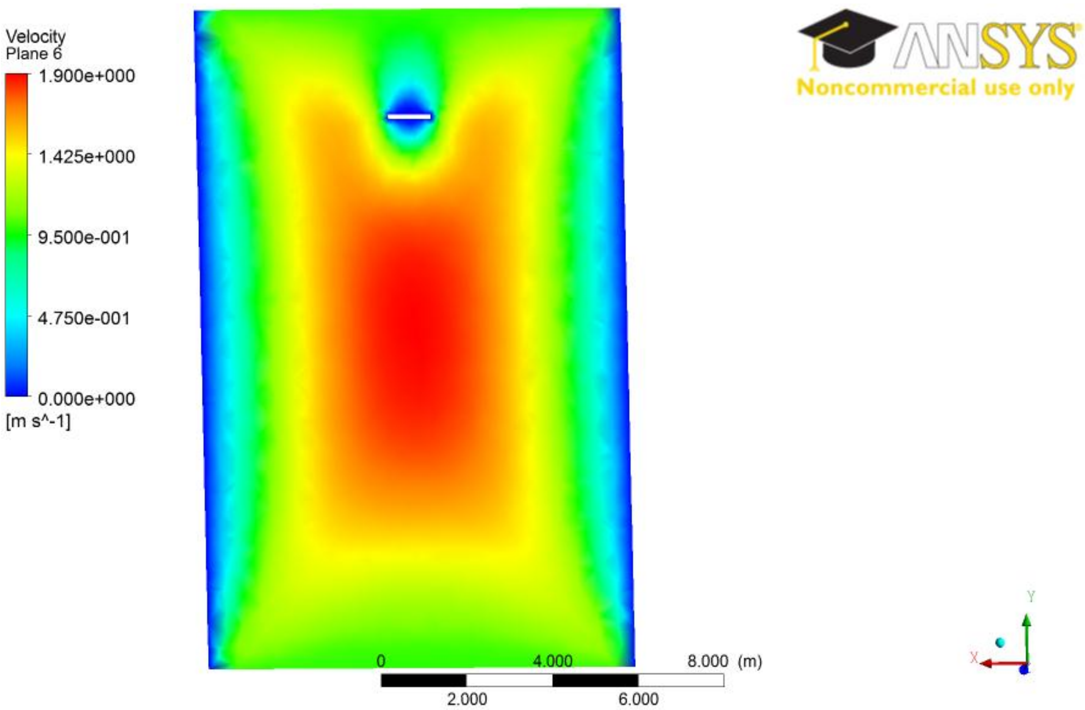

Figure 47: Velocity Contour for L/D=0.1 at Re=1

From the velocity contours, we find that velocity of the entering fluid is constant and then there is variation in velocity. The velocity of the fluid around the surface of the cylinder up to some region is zero. There is gradient in velocity around the surface for both the top and bottom face of the cylinder as can be seen from the velocity contour.

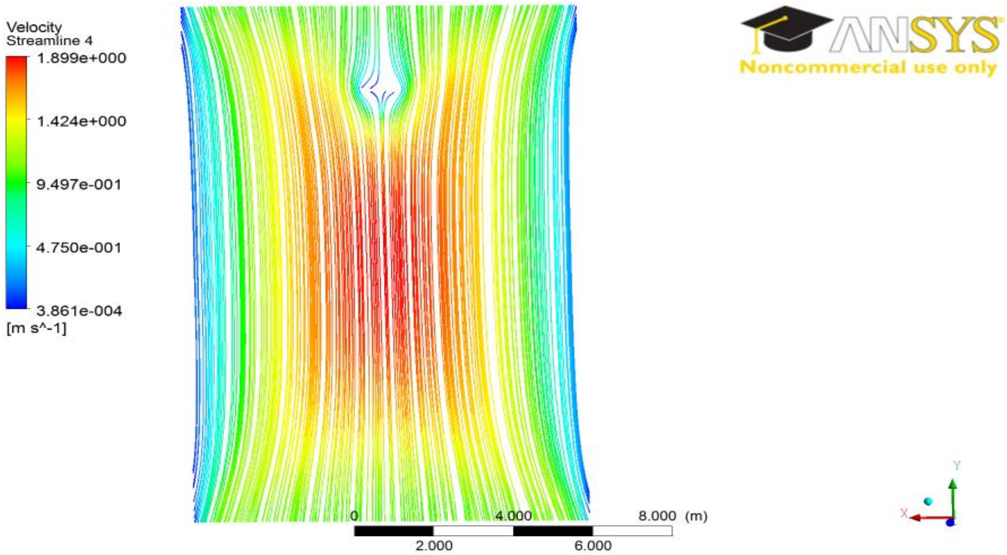

Figure 48: Velocity Streamline Contour for L/D=0.1 at Re=1

The above is the contours of velocity streamlines. It shows symmetry of the flow.

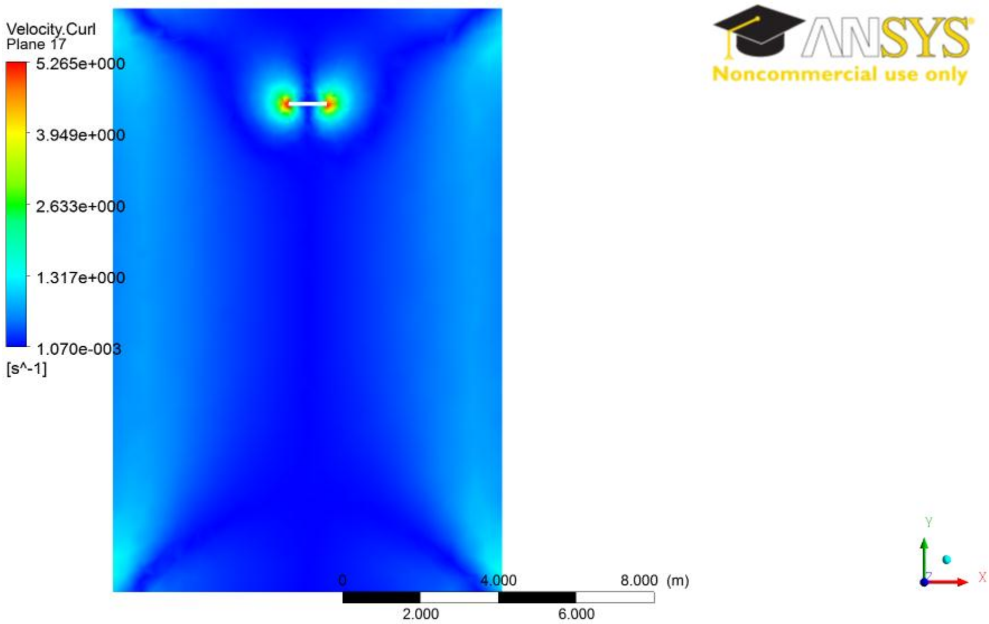

Figure 49: Vorticity Contour for L/D=0.1 at Re=1

There are steep gradients of vorticity around the walls of the cylinder. It means the circulation of fluid is more over these places.

Following are the contour plots for L/D=0.1 at Re=10

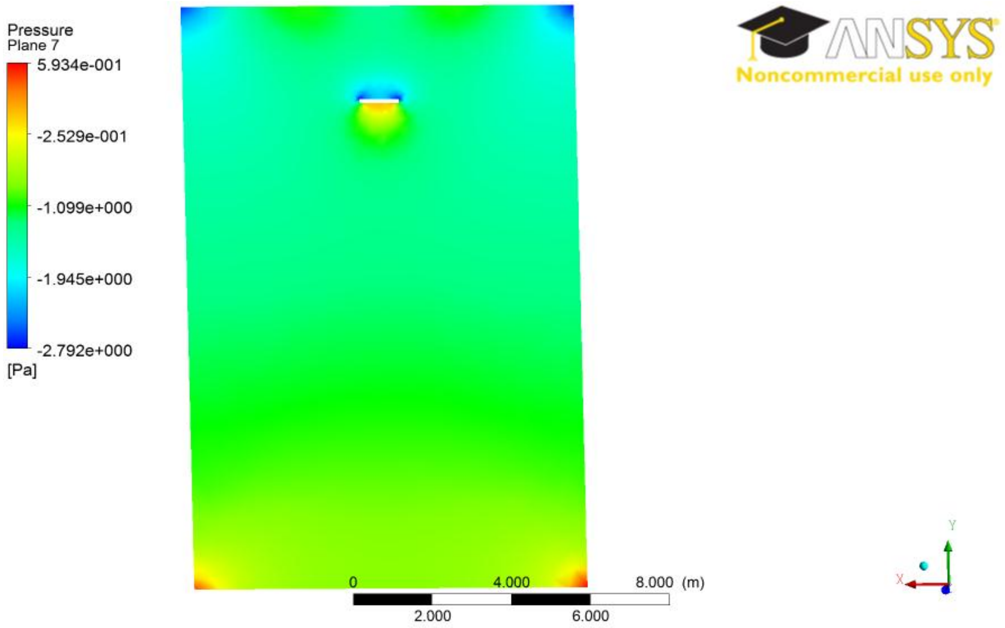

Figure 50: Pressure Contour for L/D=0.1 at Re=10

There exists some variation in pressure around top face of the cylinder. And steep variations of pressure exist around some region in the bottom face of the cylinder and then the pressure remains constant.

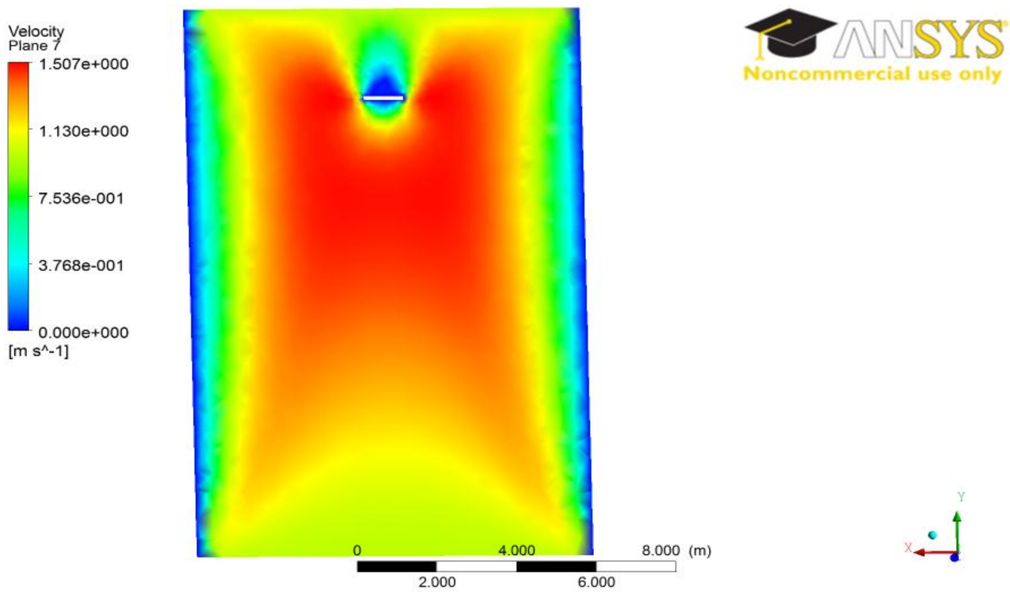

Figure 51: Velocity Contour for L/D=0.1 at Re=10

The velocity is zero around a small region of the cylinder as can be seen from the contours of the plane. And then again up to some region the velocity remains constant, then there is variations in velocity distribution.

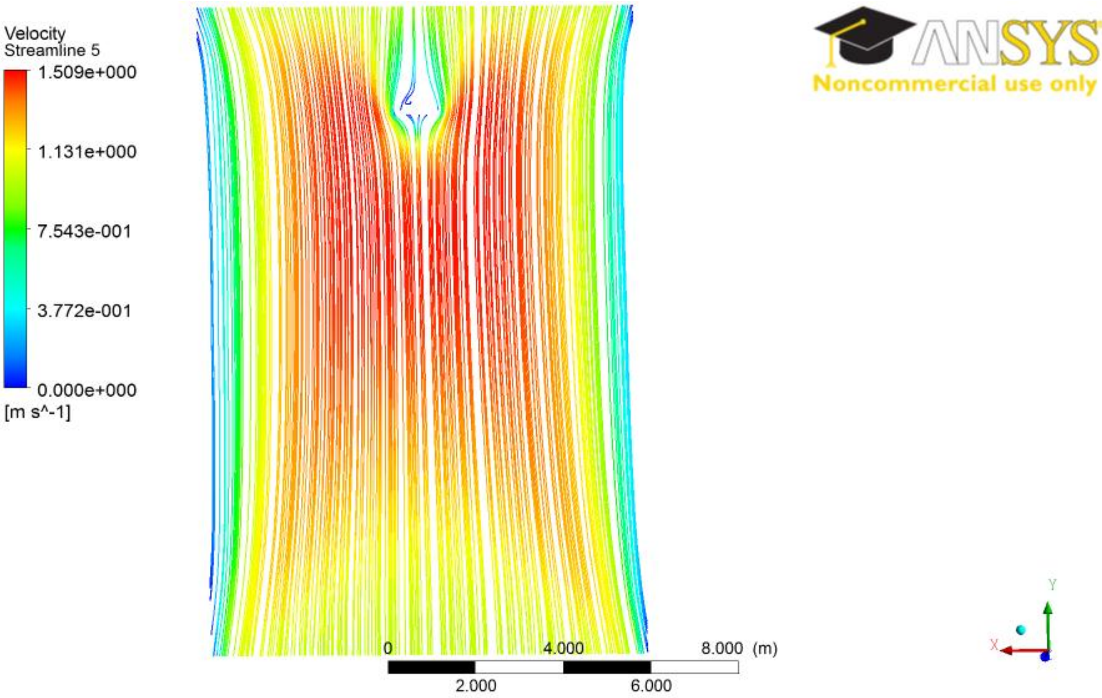

Figure 52: Velocity Streamline Contour for L/D=0.1 at Re=10

Streamlines shows symmetry of flow around the cylinder in the flow domain.

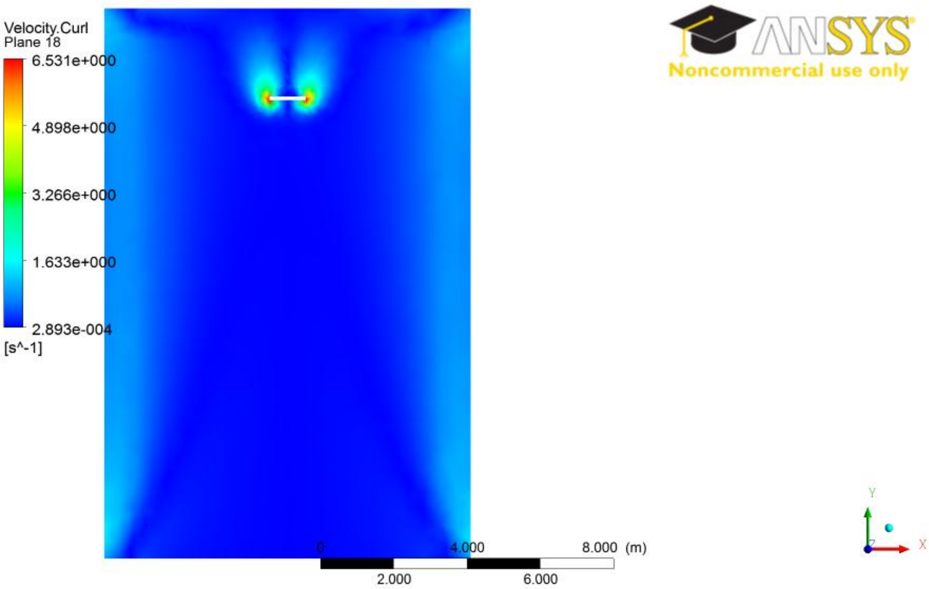

Figure 53: Vorticity Contour for L/D=0.1 at Re=10

There are steep gradients of vorticity around the walls of the cylinder. It means the circulation of fluid id more over these places. And the vorticity gradients in the upstream extends to greater region.

Following are the contour plots for L/D=0.1 at Re=100

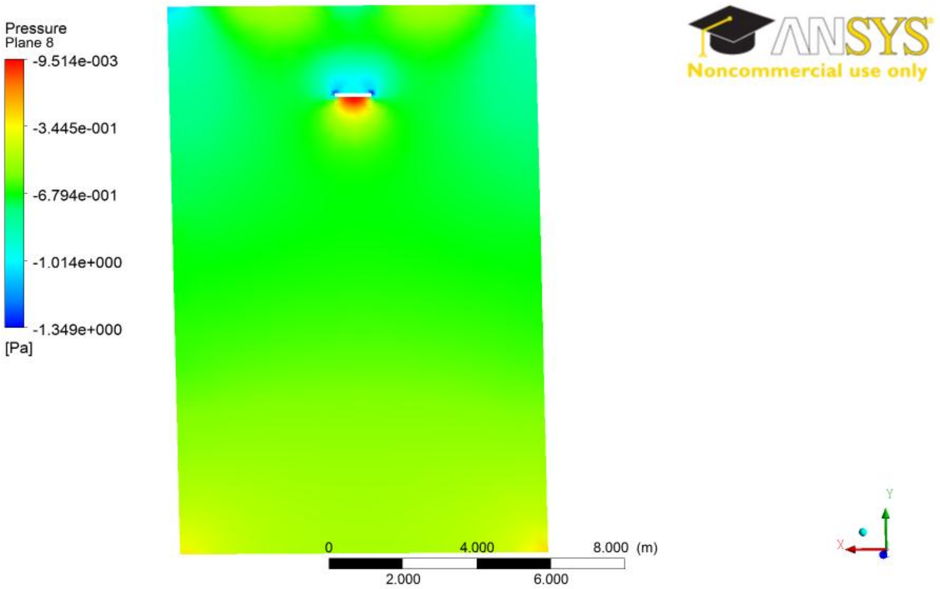

Figure 54: Pressure Contour for L/D=0.1 at Re=100

From the pressure contour we see that the pressure is almost constant around some area of the top face of the cylinder. And in the bottom face of the cylinder there is steep gradients in pressure up to some region of bottom face. Then the pressure remains constant.

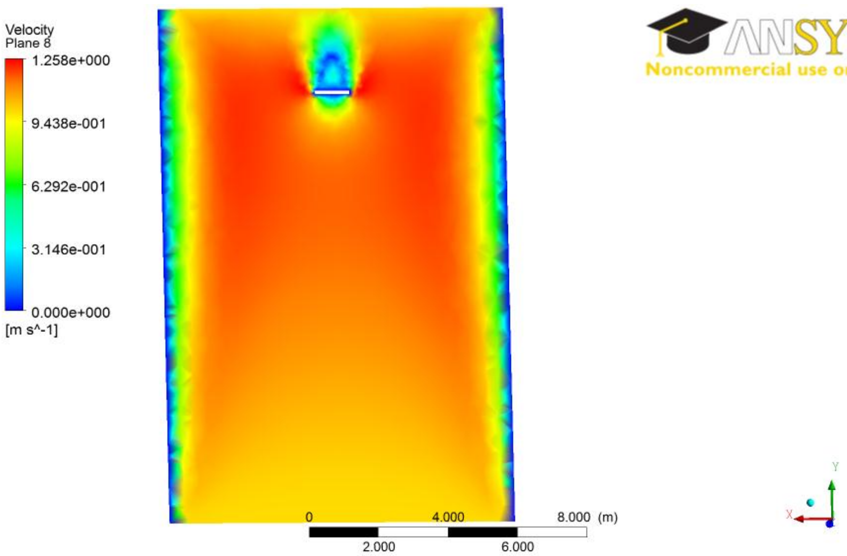

Figure 55: Velocity Contour for L/D=0.1 at Re=100

Velocity is zero, as can be seen from the contour plot, up to some region surrounding the cylinder. There is variation in velocity around the top face of the cylinder which extends up to large area in comparison to the bottom face. In bottom face also there is variation in velocity; the velocity gradually increases downstream and then remains constant. Velocity at the walls of the flow domain is zero, which shows the walls have negligible or no effect on the flow over the cylinder. And gradually the velocity increases away from the wall.

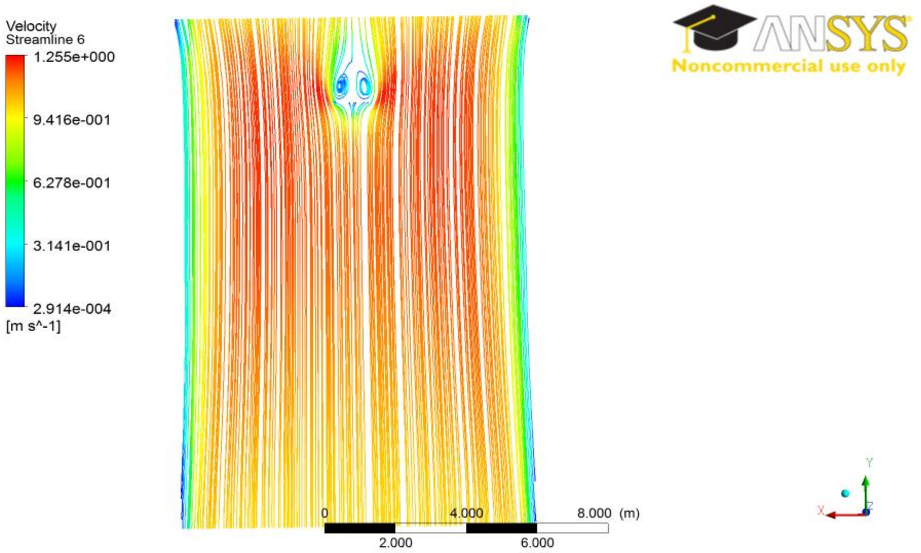

Figure 56: Velocity Streamline Contour for L/D=0.1 at Re=100

Streamlines show symmetry of the flow.

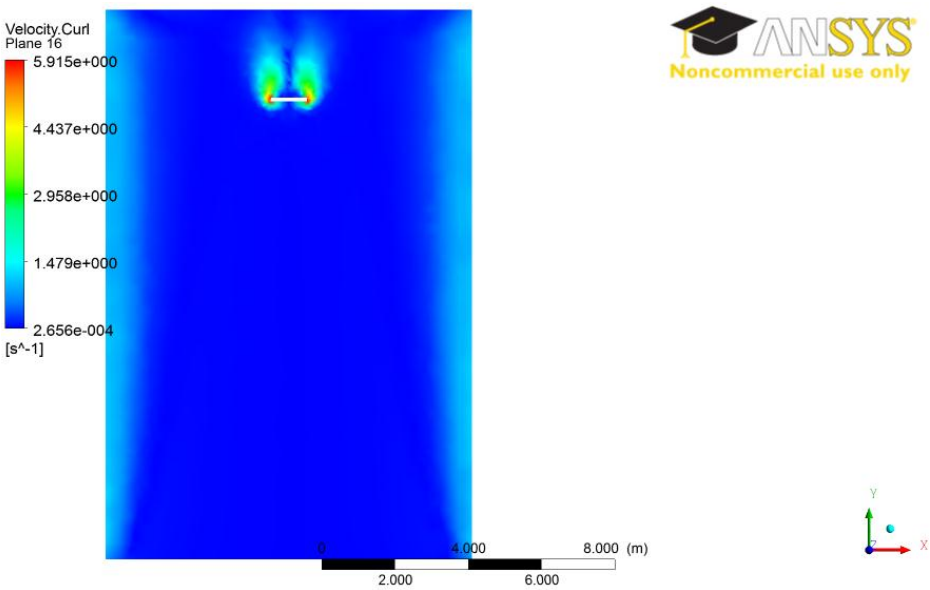

Figure 57: Vorticity Contour for L/D=0.1 at Re=100

There are steep gradients of vorticity around the walls of the cylinder. It means the circulation of fluid id more over these places. And the vorticity gradients in the upstream extends to greater region.

Following are the contour plots for L/D=0.5 at Re=1

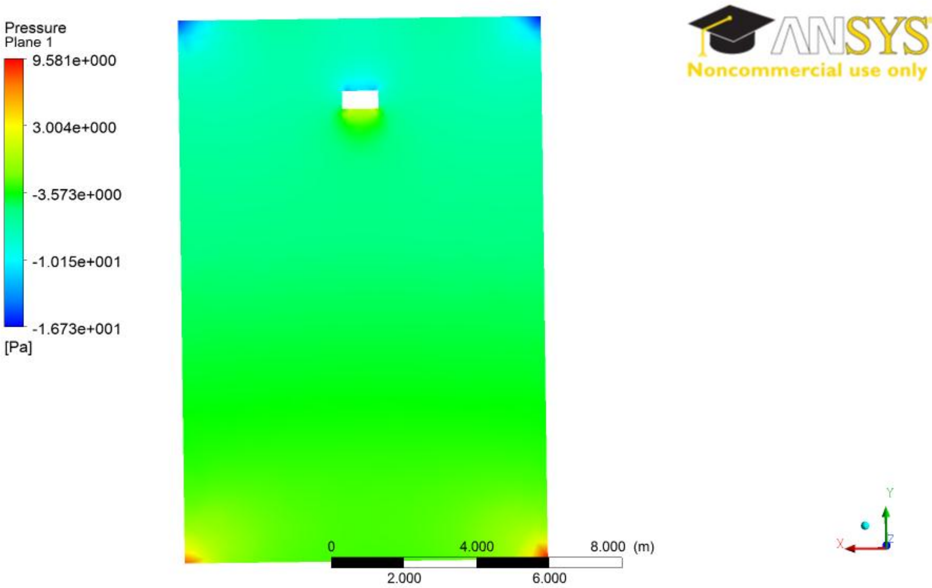

Figure 58: Pressure Contour for L/D=0.5 at Re=1

From the plot, the pressure of the inlet fluid is constant and is very low over the top face of the cylinder. At the bottom face there is some variations in the pressure. The pressure in the bottom face of the cylinder is more than that at the top face.

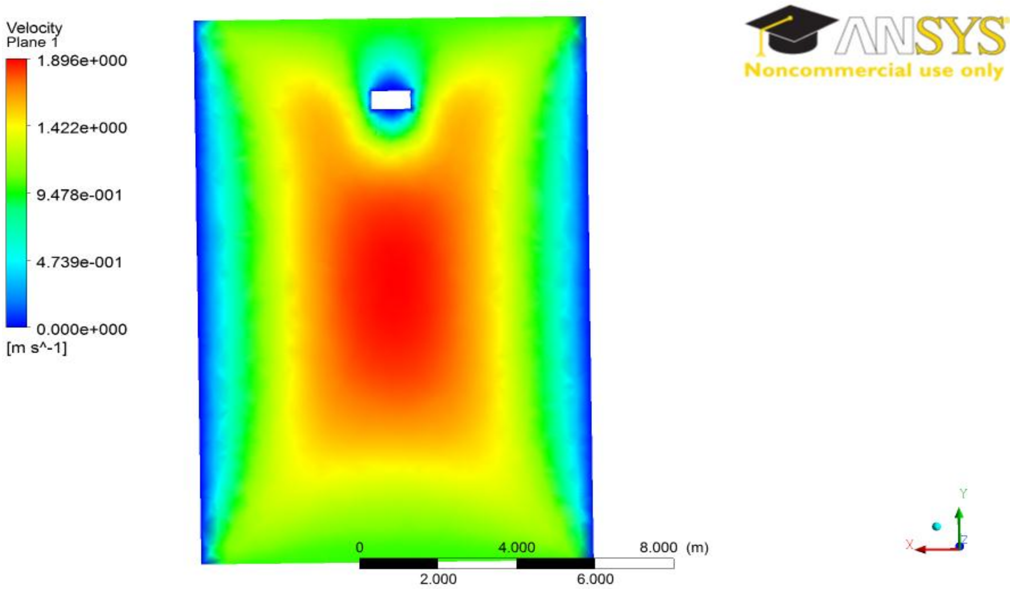

Figure 59: Velocity Contour for L/D=0.5 at Re=1

From the velocity contours, we find that velocity of the entering fluid is constant and then there is variation in velocity. The velocity of the fluid around the surface of the cylinder up to some region is zero. There is gradient in velocity around the surface for both the top and bottom face of the cylinder as can be seen from the velocity contour.

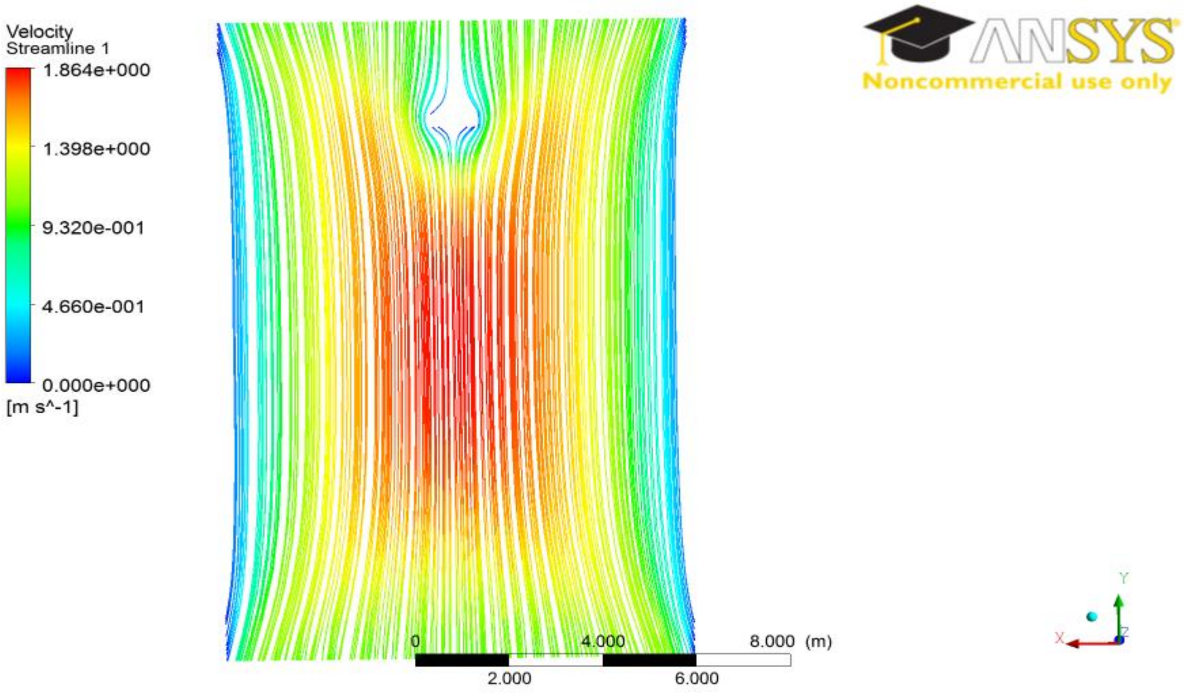

Figure 60: Velocity Streamline Contour for L/D=0.5 at Re=1

Streamlines show the symmetry of the flow.

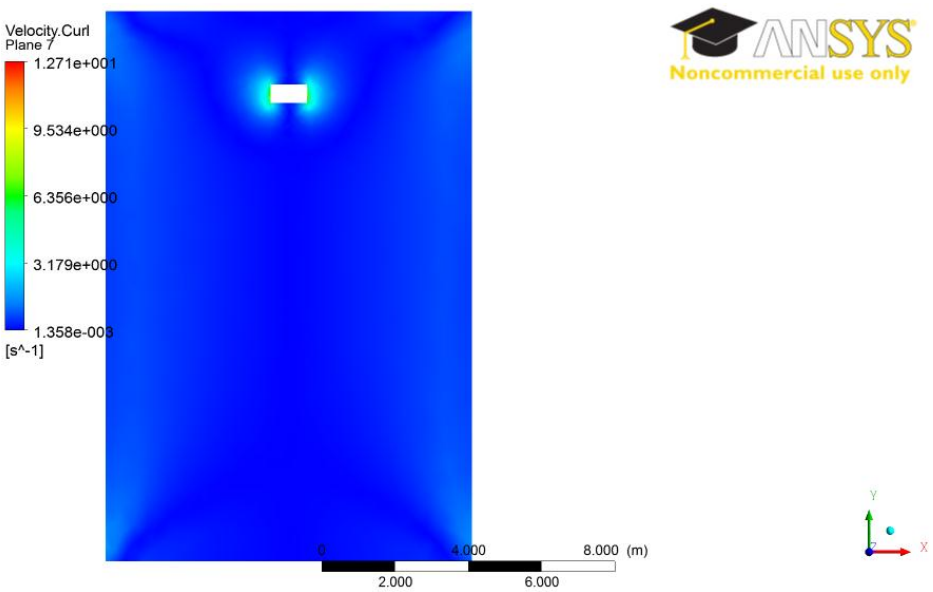

Figure 61: Vorticity Contour for L/D=0.5 at Re=1

Vorticity gradients are found around the wall of the cylinder. It means the fluid circulation is more over these places.

Following are the contour plots for L/D=0.5 at Re=10

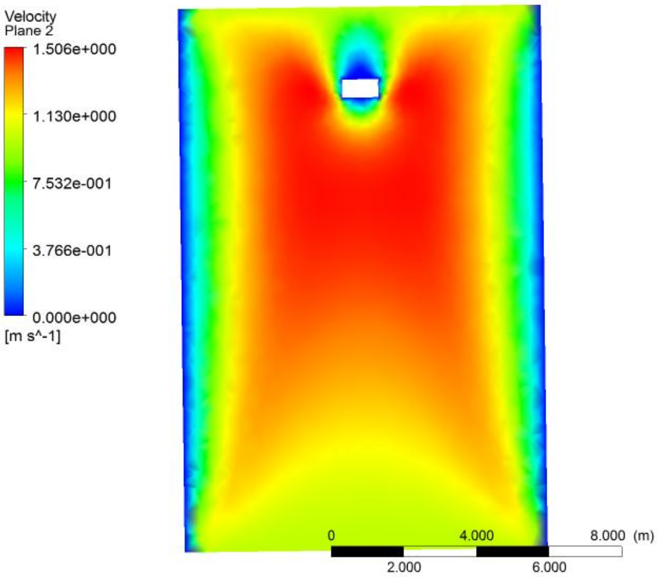

Figure 62: Velocity Contour for L/D=0.5 at Re=10

The velocity is zero around a small region of the cylinder as can be seen from the contours of the plane. And then again up to some region the velocity remains constant, then there is variations in velocity distribution.

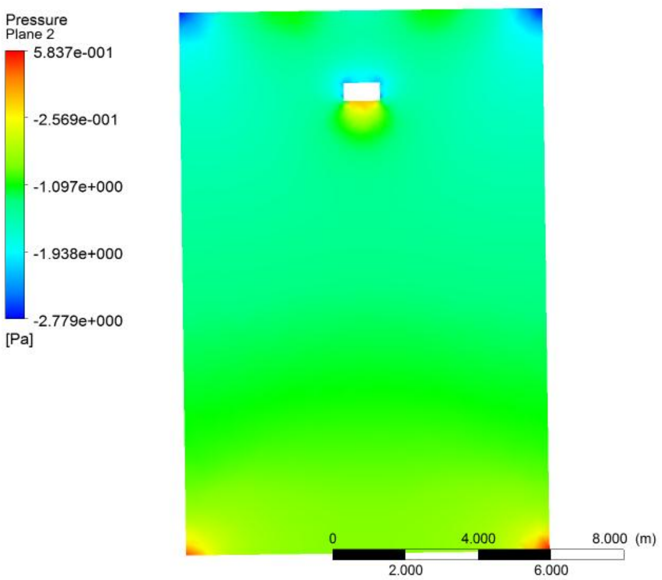

Figure 63: Pressure Contour for L/D=0.5 at Re=10

There exists some variation in pressure around top face of the cylinder. And steep variations of pressure exist around some region in the bottom face of the cylinder and then the pressure remains constant.

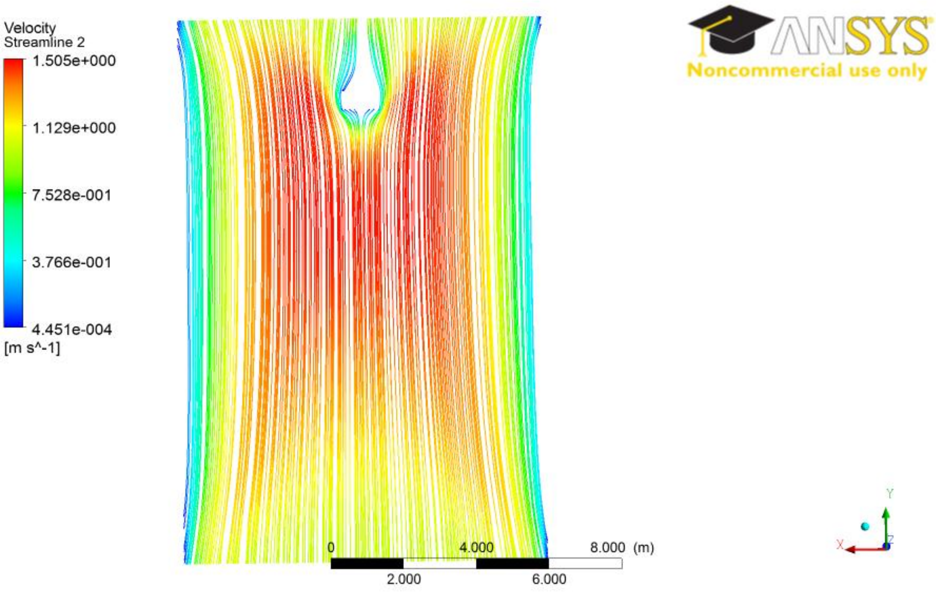

Figure 64: Velocity Streamline Contour for L/D=0.5 at Re=10

The streamlines show the symmetry of flow.

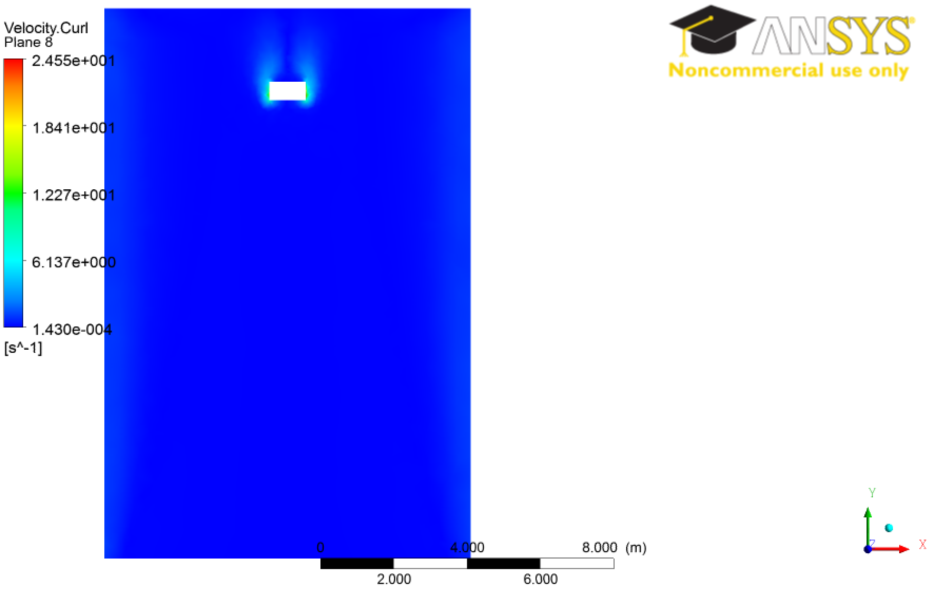

Figure 65: Vorticity Contour for L/D=0.5 at Re=10

There are gradients of vorticity around the walls of the cylinder. It means the circulation of fluid id more over these places. And the vorticity gradients in the upstream extends to greater region.

Following are the contour plots for L/D=0.5 at Re=100

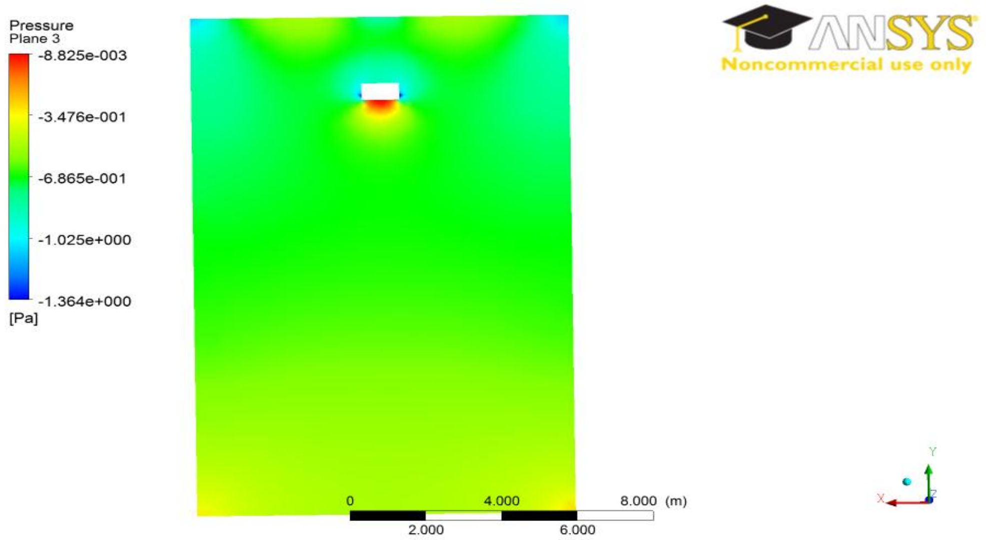

Figure 66: Pressure Contour for L/D=0.5 at Re=100

From the plot, the pressure of the inlet fluid is constant and is very low over the top face of the cylinder. At the bottom face there is some variations in the pressure. The pressure in the bottom face of the cylinder is more than that at the top face.

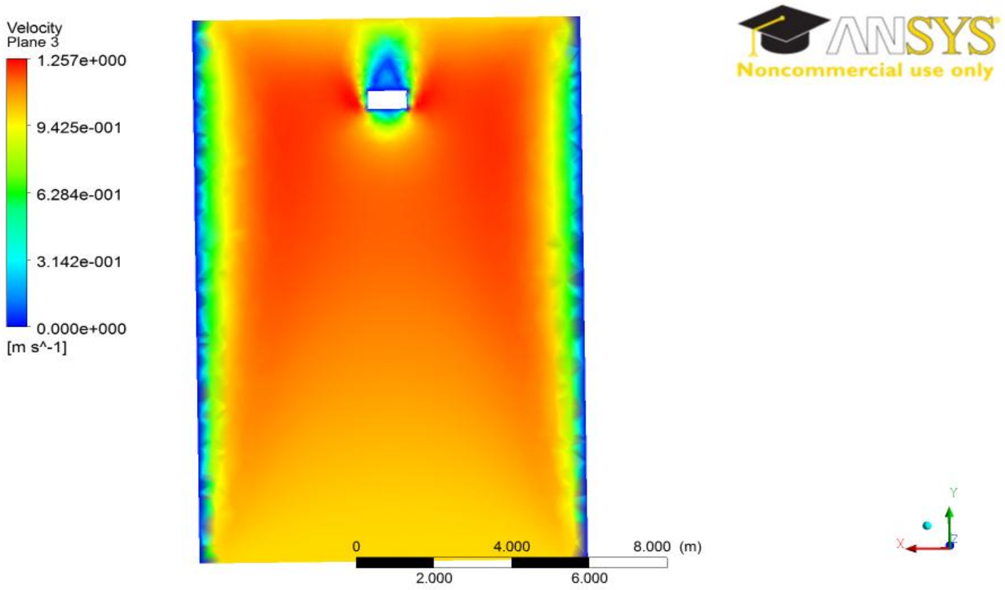

Figure 67: Velocity Contour for L/D=0.5 at Re=100

Velocity is zero, as can be seen from the contour plot, up to some region surrounding the cylinder. There is variation in velocity around the top face of the cylinder which extends up to large area in comparison to the bottom face. In bottom face also there is variation in velocity; the velocity gradually increases downstream and then remains constant. Velocity at the walls of the flow domain is zero, which shows the walls have negligible or no effect on the flow over the cylinder. And gradually the velocity increases away from the wall.

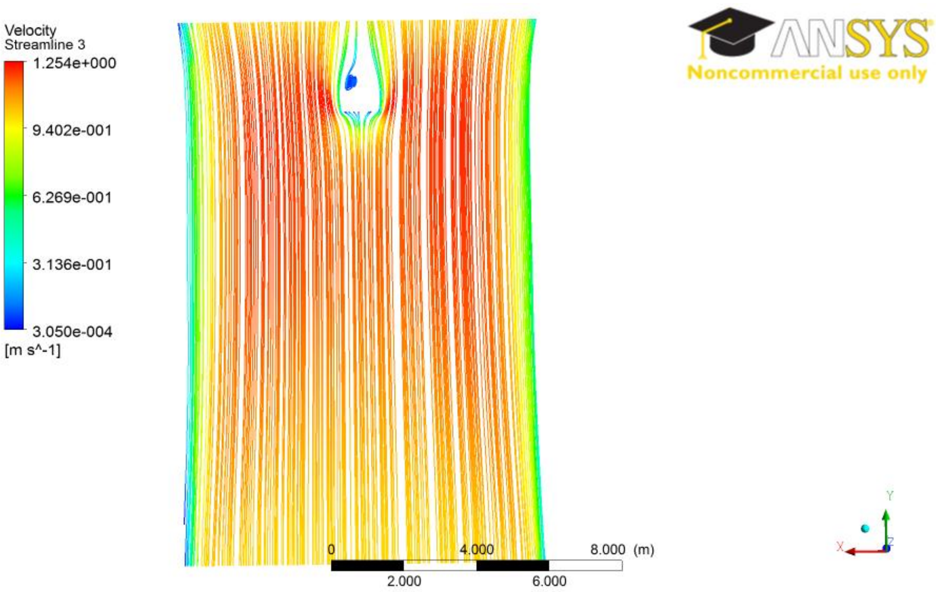

Figure 68: Velocity Streamline Contour for L/D=0.5 at Re=100

The streamlines show the symmetry of flow.

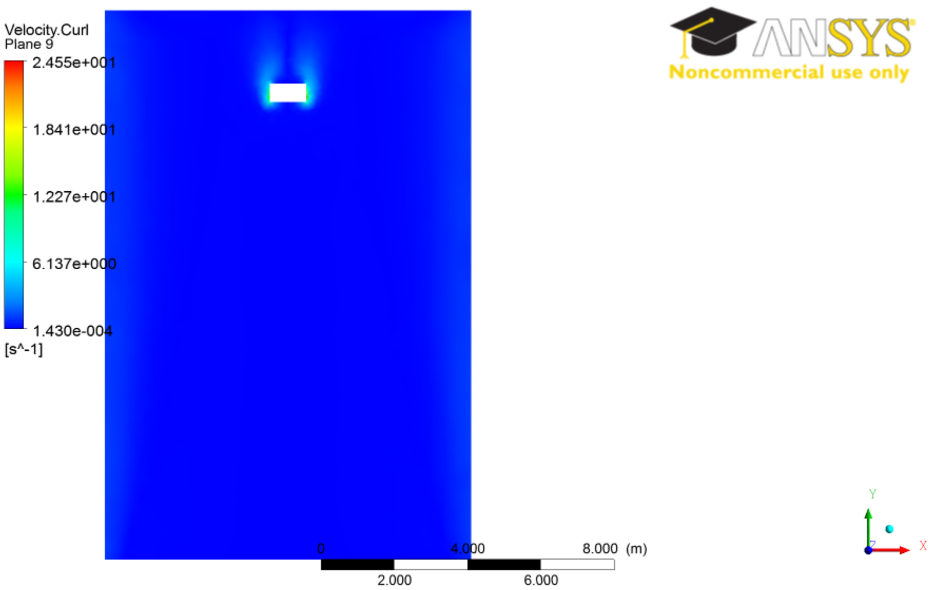

Figure 69: Vorticity Contour for L/D=0.5 at Re=100

There are steep gradients of vorticity around the walls of the cylinder. It means the circulation of fluid id more over these places. And the vorticity gradients in the upstream extends to greater region.

Following are the contour plots for L/D=1 at Re=1

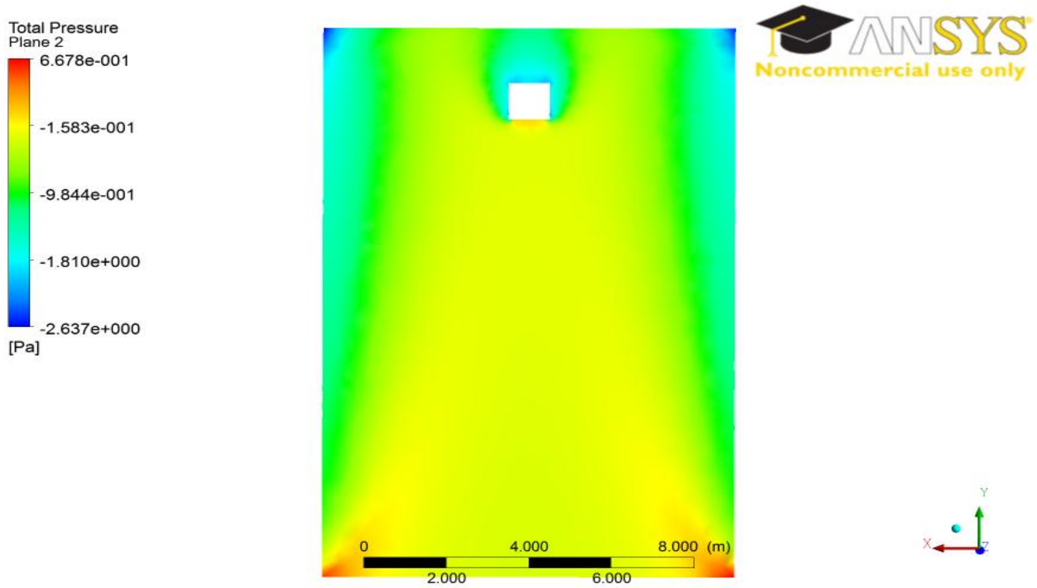

Figure 70: Pressure Contour for L/D=1 at Re=1

From the plot, the pressure of the inlet fluid is constant and is very low over the top face of the cylinder. At the bottom face there is some variations in the pressure. The pressure in the bottom face of the cylinder is more than that at the top face.

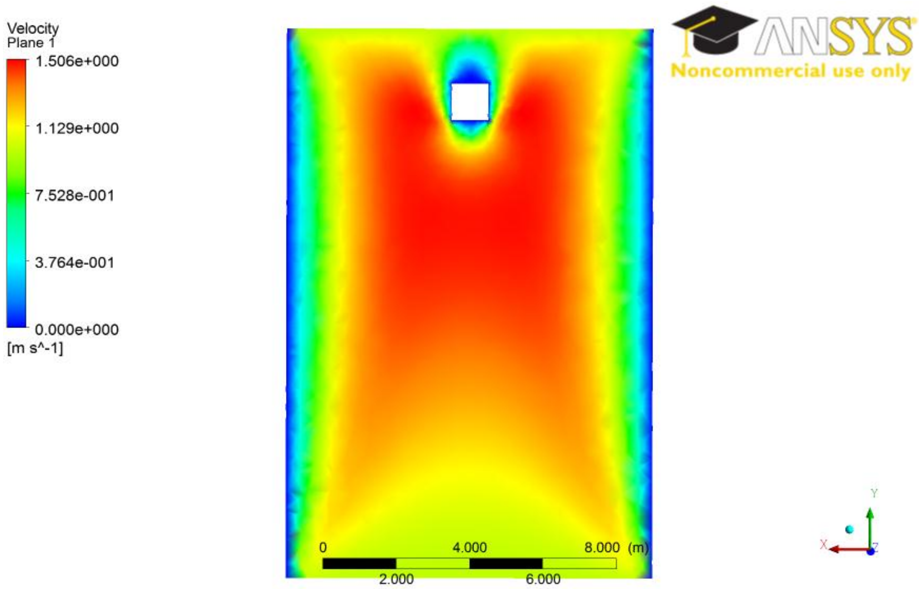

Figure 71: Velocity Contour for L/D=1 at Re=1

From the velocity contours, we find that velocity of the entering fluid is constant and then there is variation in velocity. The velocity of the fluid around the surface of the cylinder up to some region is zero. There is gradient in velocity around the surface for both the top and bottom face of the cylinder as can be seen from the velocity contour.

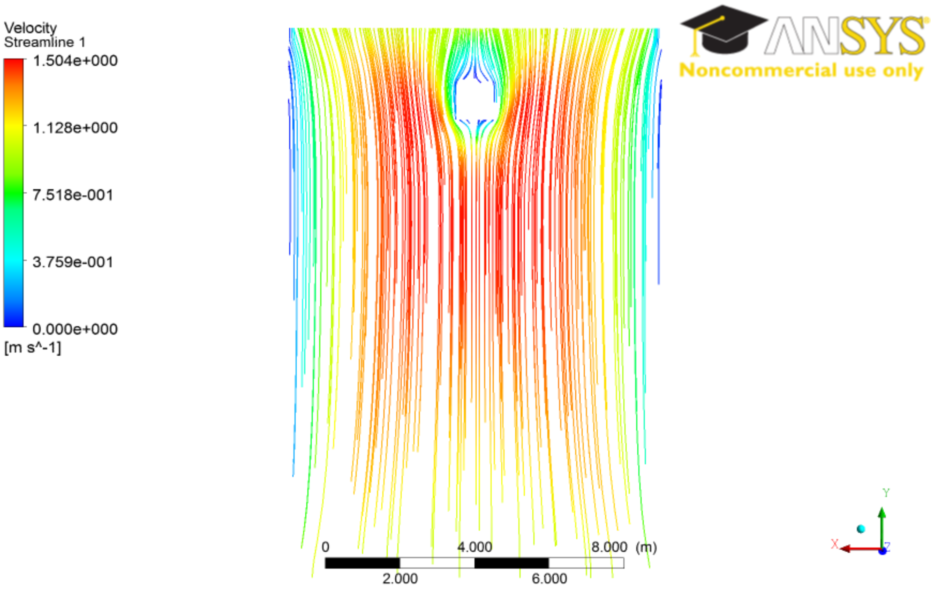

Figure 72: Velocity Streamline Contour for L/D=1 at Re=1

The streamlines show the symmetry of flow.

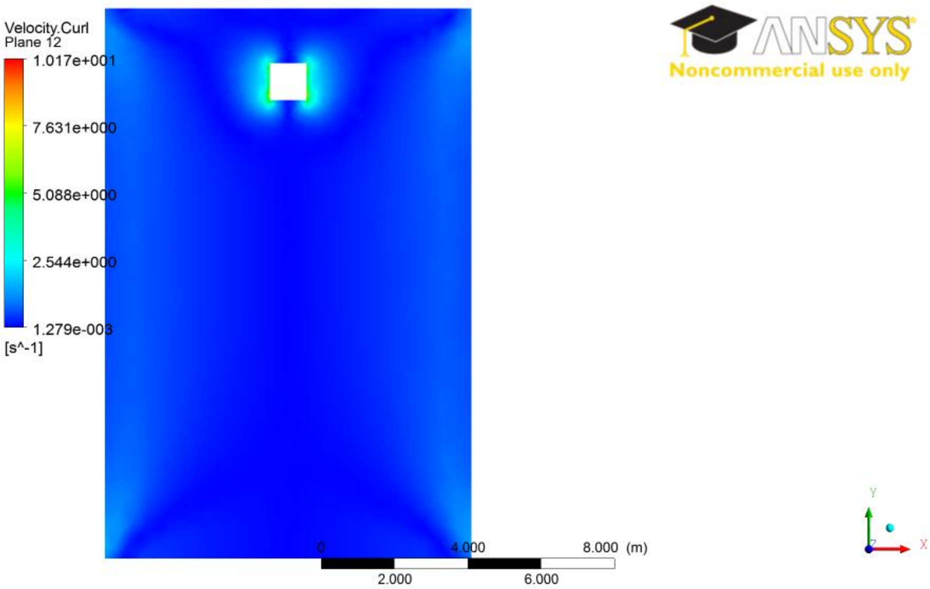

Figure 73: Vorticity Contour for L/D=1 at Re=1

There are gradients of vorticity around the walls of the cylinder. It means the circulation of fluid id more over these places.

Following are the contour plots for L/D=1 at Re=10

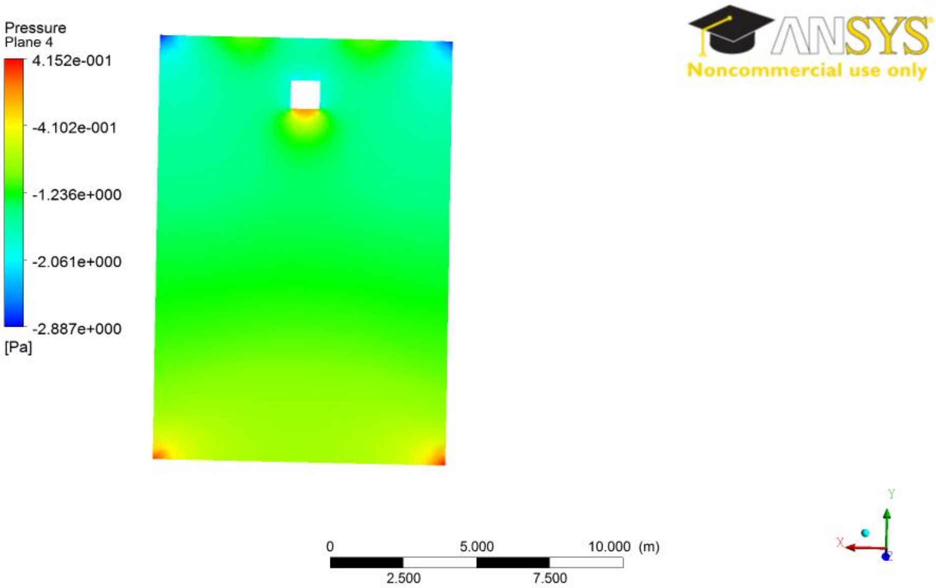

Figure 74: Pressure Contour for L/D=1 at Re=10

There exists some variation in pressure around top face of the cylinder. And steep variations of pressure exist around some region in the bottom face of the cylinder and then the pressure remains constant.

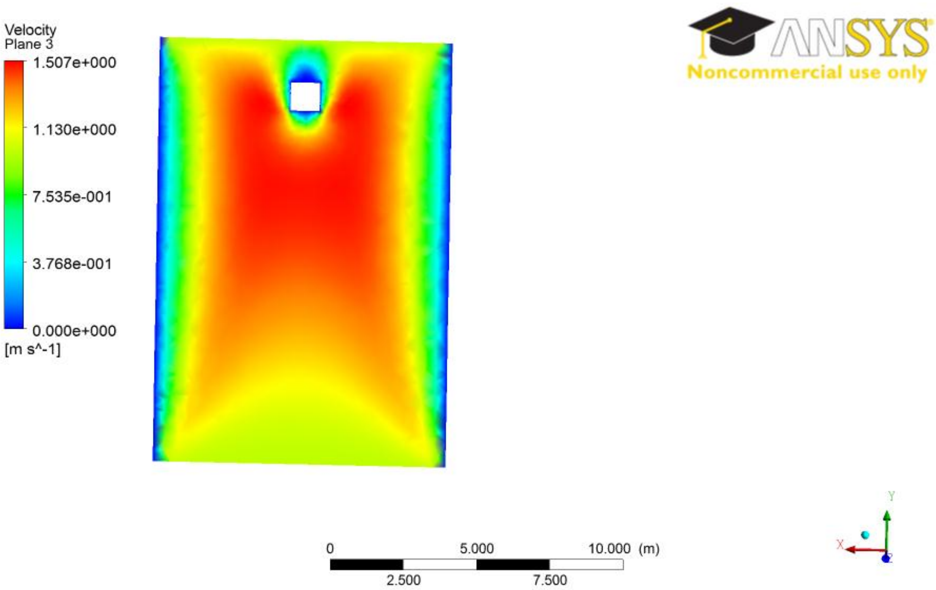

Figure 75: Velocity Contour for L/D=1 at Re=10

The velocity is zero around a small region of the cylinder as can be seen from the contours of the plane. And then again up to some region the velocity remains constant, and then there is a variation in velocity distribution.

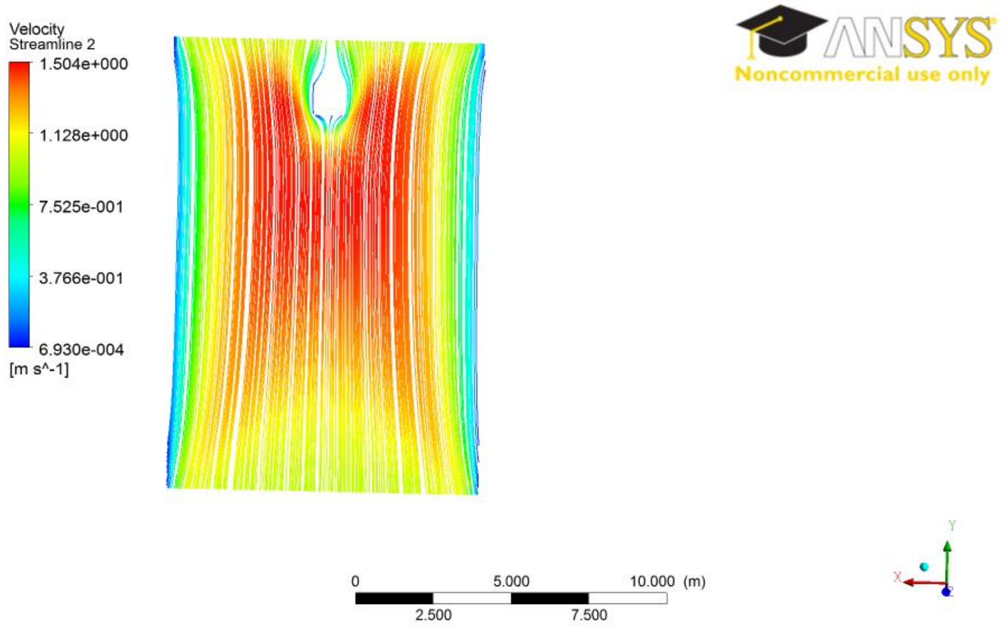

Figure 76: Velocity Streamline Contour for L/D=1 at Re=10

The streamlines show the symmetry of flow.

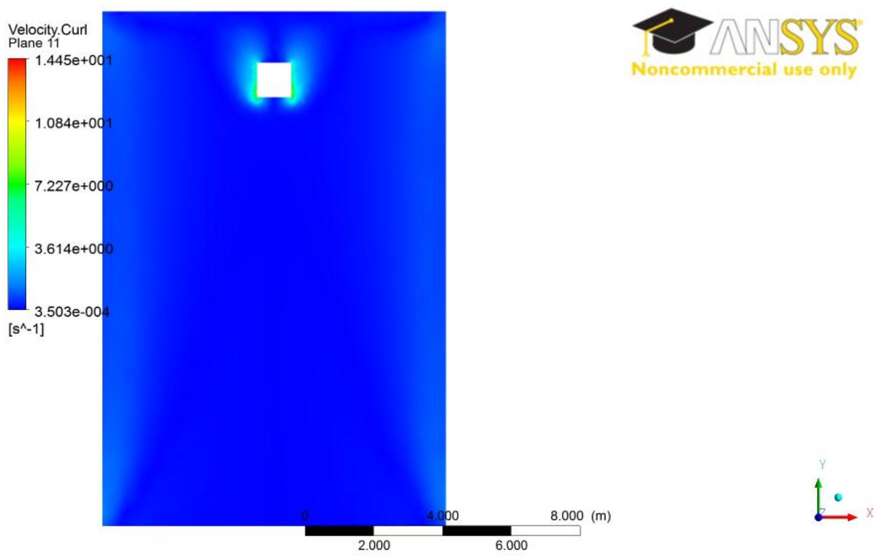

Figure 77: Vorticity Contour for L/D=1 at Re=10

There are gradients of vorticity around the walls of the cylinder. It means the circulation of fluid id more over these places. And the vorticity gradients in the upstream extends to greater region.

Following are the contour plots for L/D=1 at Re=100

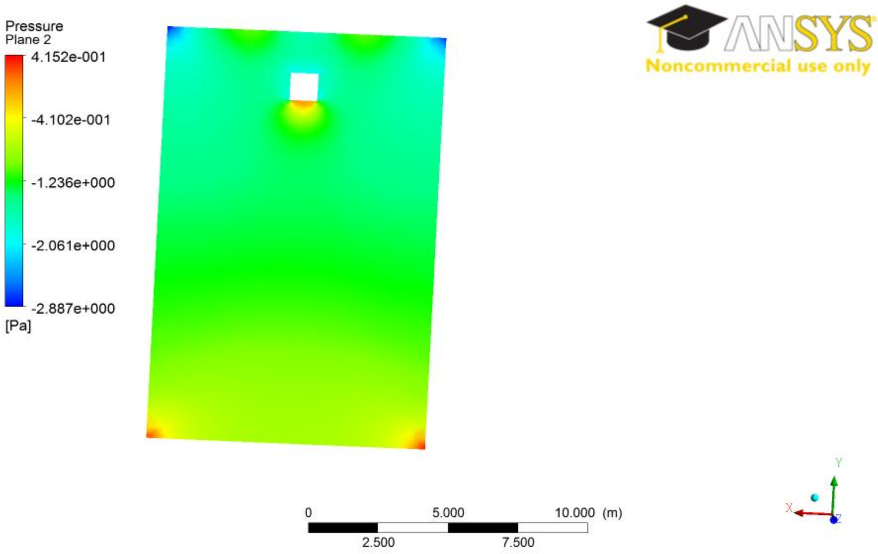

Figure 78: Pressure Contour for L/D=1 at Re=100

From the plot, the pressure of the inlet fluid is constant and is very low over the top face of the cylinder. At the bottom face there is some variations in the pressure. The pressure in the bottom face of the cylinder is more than that at the top face.

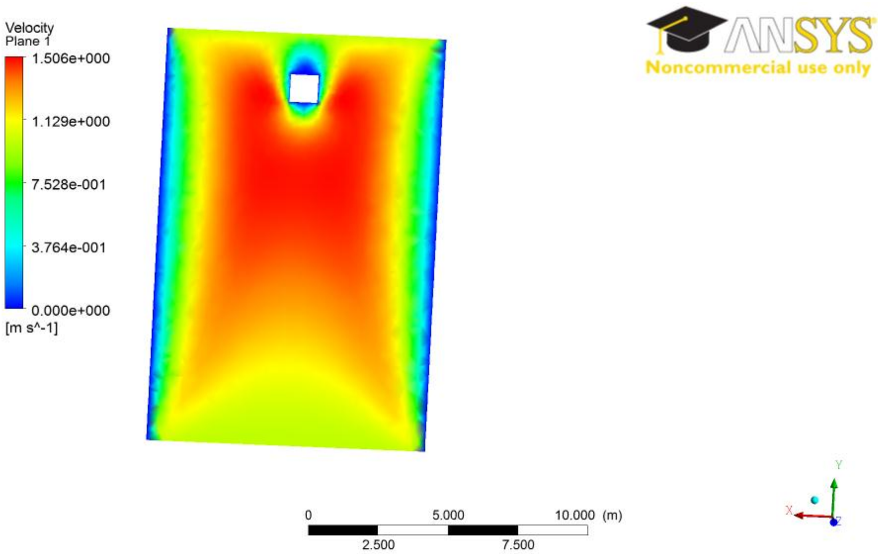

Figure 79: Velocity Contour for L/D=1 at Re=100

Velocity is zero, as can be seen from the contour plot, up to some region surrounding the cylinder. There is variation in velocity around the top face of the cylinder which extends up to large area in comparison to the bottom face. In bottom face also there is variation in velocity; the velocity gradually increases downstream and then remains constant. Velocity at the walls of the flow domain is zero, which shows the walls have negligible or no effect on the flow over the cylinder. And gradually the velocity increases away from the wall.

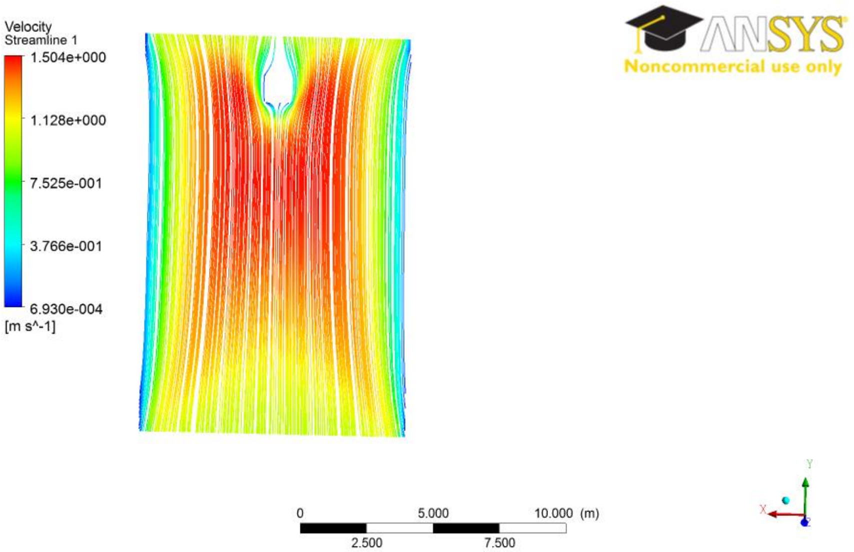

Figure 80: Velocity Streamline Contour for L/D=1 at Re=100

The streamlines show the symmetry of flow.

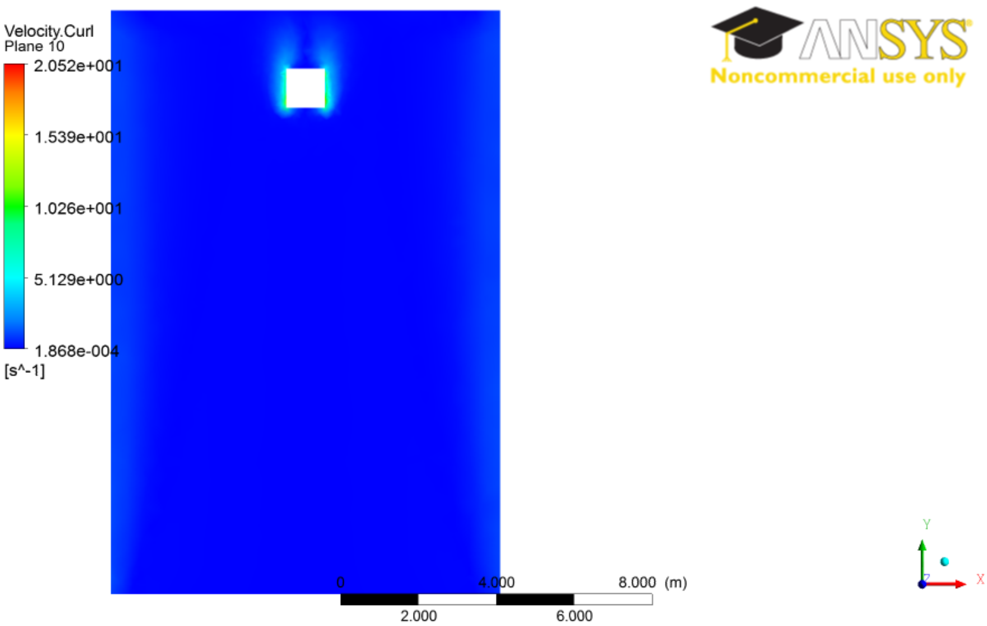

Figure 81: Vorticity Streamline Contour for L/D=1 at Re=100

There are gradients of vorticity around the walls of the cylinder. It means the circulation of fluid id more over these places. And the vorticity gradients in the upstream extends to greater region.

From the velocity contours, we can find the formation of boundary layers in the flow. And the velocity of the fluid at the interface between the solid and fluid is zero. The velocity near the cylinder surface is less. The velocity increases with distance from the plate, as is the phenomena in the flow in boundary layers. Gradually the velocity increases and reaches the velocity of inlet fluid that is 1 m /s.

Velocity at the walls of the flow domain is zero. So we can conclude that the walls have negligible or no effect on the flow over the cylinder and the selection of dimension of flow domain is apt.

In the velocity streamlines we can see formation of wakes.

5. CONCLUSION

1. Drag coefficient decreases with an increase in Reynolds number for all L/D ratios, for a cylinder.
2. The decrease in the value of drag coefficient at higher Reynolds number is comparatively lower than in the case of lower Reynolds number.
3. For a constant Reynolds number, the value of drag coefficient decreases with an increase in L/D ratio of the cylinder.
4. The values of drag coefficient of an ideal cylinder, having L=D=1, almost converges with that of sphere at constant Reynolds number.
5. The region for the above cause, the sphericity of cylinder tends to 1.
6. From pressure contours, there are steep variations in pressure in the top face of the cylinder at lower Reynolds number and negligible variations in pressure at the bottom face of the cylinder. But as Reynolds number increases, at Re=100, there is steep variations in pressure at the bottom of the cylinder and small variations in the top of the cylinder.
7. From the velocity contours, the velocity around the surface of the cylinder is zero.
8. There exists variation in velocity, both on the top and bottom face of the cylinder. The variation of velocity extends up to larger area for the top face of cylinder in comparison to the bottom face of the cylinder.
9. The velocity of the fluid at the wall of the flow domain is zero, the walls of flow domain have negligible or no effect on the flow over cylinder.
10. The vorticity plots, show large variations in vorticity near the wall of the cylinder which gradually diminishes away from wall of cylinder.
11. As the value of Reynolds number increases, the constant vorticity lines also extend to larger distance in the upstream.

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